EVALUATION OF TRAFFIC OPERATIONS AT INTERSECTIONS IN MALFUNCTION FLASH MODE

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EVALUATION OF TRAFFIC OPERATIONS AT INTERSECTIONS IN MALFUNCTION FLASH MODE

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SUMMARY

During a signal malfunction, traffic signals are operated in the flash mode. During this event, drivers are presented with one of two possible scenarios: (1) flashing yellow on the major street and flashing red on the minor street or (2) flashing red on all approaches. Yellow/red flash is the default configuration used in most locations. Yellow/red flash is utilized based on the expectation that red/red flash would produce an intolerable amount of delay. However, little research has been conducted to date on flashing operations, with exception of low-volume nighttime conditions.

A traffic signal malfunction can occur during any time of the day, potentially placing the signal into flash mode under moderate to peak traffic volume conditions. In order to assess the safety implications of these events and improve the process by which the mode of flash (yellow/red versus red/red) is selected, the research contained in this study evaluated driver behavior and the operational characteristics of intersections operating in malfunction flash mode under a wide spectrum of traffic demands.

Analysis of field data collected at thirteen study intersections in the Atlanta, Georgia area found that confusion exists among drivers approaching a signal in flash mode. The analysis found that a significant percentage of vehicles stop on a yellow indication. It was seen that an intersection flashing yellow/red could operate as a two-way stop or four-way stop, potentially transitioning between these two alternatives on a minute-by-minute basis. This creates an increased potential for crashes and further compounds the problem of driver expectancy by creating a constantly changing control environment. The stopping on yellow also introduces additional delay, which reduces the

operational benefit of utilizing the yellow/red flash mode. Furthermore, a high level of traffic violations was observed for the flashing red indications for both yellow/red and red/red flashing operation.

Based upon the study results, providing one consistent mode of flashing operation may be a reasonable solution to improving driver expectancy and safety. Red/red flashing operation is the preferred mode as it provides a reduction in vehicle speeds for all vehicles while also reducing the variability in the number of vehicles stopping. Additionally, the issue of driver expectancy at signals with yellow/red flash would be removed allowing for a more consistent message to the public that all flashing signals should be treated as a four-way stop.

CHAPTER 1

INTRODUCTION

Road safety has been identified by the U.S. Department of Transportation (U.S. DOT) and many state DOTs as the most important transportation priority in the U.S today. Although crashes can occur for many reasons, one of the most significant is driver uncertainty when facing unexpected road conditions. Driver expectancy is the predisposition of drivers to believe that different parts of the traffic system (geometric design, traffic control, actions of other drivers, etc.) will behave or be implemented in a certain way. A driver's expectancies influence the driver's ability to accurately process the information around them and safely respond to traffic situations [1]. Driver expectancy is critical to the safe operation of intersections where an understanding and adherence to regulations and the "rules of the road" guide driver behavior. This study examines instances where drivers are exposed to the unexpected event of a traffic signal operating in flash mode, which can lead to erratic driver behavior and potential safety problems.

There are four primary categories of intersection signal flash: programmed (pre-planned flash, typically set by time of day), police panel (a police officer places a signal in flash using the police panel interface), technician (a signal technician places the signal in flash using a switch inside the cabinet), and malfunction (the signal is placed in flash by the malfunction monitoring unit). While in flash, there are two possible signal indications that may be presented to the motorist. These options are a red flashing signal on both the major and minor approaches to the intersection (red/red flash) or a flashing yellow indication on the major street and flashing red indication on the minor street (yellow/red flash). Regulations for vehicles traveling through a flashing signal may vary slightly in language among the states, but typically require vehicles to come to a stop at a flashing red indication and proceed with caution at a flashing yellow indication Section 40-6-23 of the Unannotated Georgia Code [2]states that flashing signal indications shall have the following meanings:

> "…When a red lens is illuminated with rapid intermittent flashes, drivers of vehicles shall stop at a clearly marked stop line… …When a yellow lens is illuminated with rapid intermittent flashes, drivers may proceed through the intersection or past such signal only with caution."

Selection of the mode of flash is typically done by rule of thumb, with the major street assigned a flashing yellow indication and minor street a flashing red indication unless circumstances, such as sight distance or crash history, prompt consideration for red/red flash. This rule of thumb is in part based upon prior research completed for low volume nighttime programmed flash. Since the other three categories of flashing operation could occur at any time of the day, including under higher volume conditions, the prior research may not be applicable to those conditions. Further, the 2003 Manual on Uniform Traffic Control Devices (MUTCD), expresses no preference for the mode of flash (yellow/red versus red/red). Therefore determination of the appropriate mode of flashing is typically based on engineering judgment, with a limited knowledge base upon which to make the decision.

1.1 Study Need

Driver expectancy and safety are two of the concerns that prompted this study. Under flashing conditions a driver facing a red indication may not receive a visual signal cue as to whether the conflicting traffic is controlled by flashing red or yellow, leading to potential confusion and hazards. For example, a driver facing a flashing red indication may delay their crossing as a result of their uncertainty of the cross street control, even though conflicting street traffic is also facing a red indication (red/red). In the case of yellow/red flash, the driver facing the red indication may enter the intersection (even though the conflicting traffic faces a yellow indication) under the belief that the conflicting traffic is facing a red indication and is also required to stop. Also, even when a driver is able to determine the flash mode of the conflicting movement it is unclear whether many drivers understand that vehicles facing a flashing yellow are not required to stop. Today's driver has no basis for arriving at an expectancy as to the type of flash mode or the behavior of other drivers at a flashing signal, a hazardous situation that urgently needs to be addressed by the profession.

Of the four types of flash, programmed flash may be avoided entirely and the hazards of police panel flash may be reduced as a police officer is on the scene to direct traffic. Technician and malfunction flash present the drivers with the situation described above where a lack of driver expectancy may present a hazardous situation. The type of flash used for each intersection, red/red or yellow/red, is dependent on the agency responsible for the timing and maintenance of the signal. Malfunction flash may also occur at any time during the day, resulting in an unexpected significant reduction in intersection capacity. Under moderate and high traffic demand this reduction may lead to significant congestion expanding well beyond the local intersection. In addition, intersections operate in malfunction flash mode until a technician is dispatched to reset the signal. Therefore, a prolonged response time could lead to significant operational impacts.

The research described in this thesis is the initial phase of a larger project that will develop: recommendations by which the occurrence of technician and malfunction flash may be minimized, criteria for when to use red/red and yellow/red flash, and public education material to inform drivers of proper operations through intersections with malfunctioning traffic signals

1.2 Study Objectives

This research project addresses an existing gap in the research literature related to intersection operations under malfunction flash conditions and lays the foundation for the development of updated standards for the traffic signal control during malfunction flash operation. This effort centers on intersection performance while in malfunction flash mode, quantifying the potential operational impacts of flashing operations under varying traffic demands through the collection and analysis of a significant set of field data. As part of this effort, observed versus expected driver behavior is examined, where expected behaviors are based upon prior documented research efforts.

1.3 Study Overview

Field data collection was conducted on an "on-call" basis, with data collection personnel traveling to intersections operating in malfunction flash mode to collect data.

The primary method of traffic operations data collection was via video. Collection of video data allowed for gathering of traditional data such as traffic volumes and turning movement counts. However, the video data also provided the opportunity to examine the behavioral components of drivers at signals in flash mode. For example, are drivers stopping, slowing down, or maintaining their current speed when facing flashing red or yellow signals. (As flashing operation may be a hazardous condition it should be noted that intersection signal control was never manually placed in flash as part of this study. All data was collected at intersections already in malfunction flash when the data collection personnel arrived and the presence of a malfunctioning signal was always immediately reported to the appropriate public agency.)

After each video was recorded, the data was reduced utilizing a Microsoft Excel based data logging program specifically developed for this study, which created an activity record for each individual vehicle at the intersection. The database record of the video was then analyzed to evaluate operational characteristics.

This report will provide an overview of the research activities undertaken in an effort to collect information on signals operating in malfunction flash mode. The major study activities included the following:

1.3.1 Literature Review

The initial work effort was focused on identifying previous research and literature on the subject of flashing signals. These documents were used to determine current practices for the use of flashing signals and to develop an understanding for how existing guidance was developed. The literature review revealed that most of the prior studies of flashing operation were limited to late night/early morning hours under low volume conditions. No literature was found documenting operational characteristics of signals in malfunction flash. This helped to establish the research need, with other prior studies of flashing signal operations used to establish the study scope. The results of the literature review are summarized in Chapter 2 of this report.

1.3.2 Field Tests of Malfunction Flash Operation

Chapter 3 of this report describes the data collection procedures undertaken for gathering field data at signals operating in malfunction flash. A detailed methodology for data reduction is provided, including a discussion of quality control measures taken to verify data accuracy. Traffic volume and geometric characteristics are also summarized for each intersection evaluated in this study.

1.3.3 Operational Analyses

A variety of analyses were undertaken as part of this study to evaluate the operational characteristics of signals operating in malfunction flash mode. Analysis was conducted to identify driver behavior at flashing signals under varying traffic volumes. Tendencies for drivers to stop at flashing signals were evaluated based upon minor street volumes and the presence (or absence) of a minor street vehicle. Observations from the data collection are summarized along with conclusions drawn from each portion of the analysis, which is presented in Chapter 4.

CHAPTER 2

LITERATURE REVIEW

In recent years, traffic signal equipment and operations have become increasingly sophisticated in response to an ever-growing population. However, research and policies for signals in malfunction flash operation have changed little, even though a malfunctioning signal creates a potentially confusing situation for drivers and a reduction in safety. Malfunction flash has been treated as a random event that cannot be controlled, with the subject of malfunction flash operations receiving little attention within the traffic signal professional and research communities.

Policies on flashing signal operation date back to the 1935 Manual on Uniform Traffic Control Devices (MUTCD). However, studies of flashing signal operations and safety mostly occurred from the late 1970's through the early 1990's. Little research has been conducted on flashing signal operation within the last decade with most of the prior research focused on program flash, that is, flashing operation that is scheduled at a signal for a specified time of day. Program flash is typically limited to late evening or early morning hours when the intersection is operating under low volume conditions.

The demand conditions under which malfunction flash may occur may differ significantly from the demand conditions typical during programmed flash operation. Malfunction flash operation may occur at any time during the day, potentially exposing the periods of highest intersection demand to flashing operation. No research was found documenting medium to high volume intersection operation while in flash mode. The operational analysis that is available typically assumed that a flashing signal would operate as a two-way or all-way stop, depending on whether the signal was operating in yellow/red or red/red flash, respectively. Unfortunately, no literature has been found that validates these assumptions, to the contrary, field observations reported within the literature seem to contradict these assumptions. It is unclear whether the operational performance findings in the literature are applicable to malfunction flash conditions, as intersection volumes may significantly exceed those studied.

2.1 Description of Previous Studies on Flashing Signal Operations

The following is a brief summary of several key research documents pertaining to the topic of flashing operation. The first two documents provide the foundation for much of the best practices currently utilized within the United States.

2.1.1 Federal Highway Administration Study (1980)

In the late 1970's, the Federal Highway Administration conducted a series of investigations into traffic performance at intersections under signal control that was published in a four-volume series entitled *A Study of Clearance Intervals, Flashing Operation, and Left-Turn Phasing at Traffic Signals* [3]. Volume three of this series is dedicated to traffic operations at a flashing signal. The study provides a comprehensive presentation of the issues relating to flashing traffic signal operations and is the primary source for many local and state policies on flashing operation. The report includes a broad literature search dating back to the 1934 MUTCD along with a review of the current state laws. Driver surveys were conducted to investigate whether drivers understood the flashing yellow and flashing red displays. The surveys indicated a high level of understanding for the display that was presented to them, but a low level of understanding for what traffic would do on the cross-street.

Field tests of flashing operation were conducted at 94 locations throughout the country, with the majority of locations in California and others in the states of Illinois, Minnesota, Ohio, Pennsylvania, and Delaware. Study intersections were selected to find a variety of geometric, traffic, and signalization characteristics. Field tests were used to evaluate vehicle conflicts, traffic violations, spot speeds on the approaches, and stopped time delay for vehicles at signals in both flash and normal signal modes. For the nighttime conditions evaluated, nearly all of the study intersections had a two-way flow rate below 400 vehicles per hour (vph), with the majority of intersections below 200 vph. Crash analysis compared before and after data for intersections where the signal operation had been changed from normal operation to flash or from yellow/red flash to red/red flash. These results showed that flashing yellow/red operation, in general, significantly increase the hazard of driving at night. With a major exception being for very low volume conditions where the major street two-way volume is less than 200 vph or the ratio of the two-way volume for the major vs. minor streets is greater than 3 to 1.

2.1.2 Texas Transportation Institute (1993)

A study [4], conducted over a 2-year period by the Texas Transportation Institute (TTI), for the Texas Department of Transportation and Federal Highway Administration, evaluated flashing signal control from an operational and safety standpoint. In addition to the study report, the findings were also reported in the ITE Journal [5] and the Transportation Research Record No. 1421. The findings of this study were used to develop a broad series of guidelines addressing the conditions under which it is appropriate to place traffic signals in flashing operation, and the selection of the flashing mode (yellow/red or red/red). The study included a comprehensive literature review of studies related to flashing signal operation, with most of the referenced studies focused on the topic of programmed flash. Research included a user survey of current practice for flashing signals and analysis of operations and safety in comparison to other modes of signal operation.

This study provides specific recommendations for flashing operation under a variety of conditions including: nighttime (low-volume) conditions, prior to signal turn-on or removal, signal malfunction, adverse weather, and within school areas. A primary finding of the study (subsequently published in the ITE Journal [5] article) was that there are no clear advantages to using flashing operation instead of normal operation. Furthermore, flashing operation generally should not be used unless an engineering study indicates that flashing operation would be of greater benefit than normal operation. Conditions where flashing operation could potentially be more advantageous were identified as: during preemption at railroad-highway grade crossings, prior to initial installation or signal removal, as the result of the conflict monitor being activated, during maintenance or construction activities, or during certain low-volume conditions. It also mentioned that: "The effective use of flashing operation seems highly dependent upon the specific circumstances under which it is being used. As a result, it is difficult, if not impossible, to develop guidelines that can be effectively applied to all situations."

2.1.3 Parsonson and Walker (1992)

Parsonson and Walker [6] summarize a study conducted by the Georgia Institute of Technology (Georgia Tech) to investigate malfunction flash operation. This research was prompted by a serious accident that occurred after a tripped conflict monitor initiated flashing operation at a signal. The research effort for this study focused primarily on the effect that sight distance has on safety at flashing signals. Observations of a number of signals in Atlanta, Georgia revealed ten intersections with insufficient sight distance based upon AASHTO criteria, each utilizing yellow/red flashing operation. The study also identified potential conflicts in the technical literature, such as the MUTCD advising that it is normal for a flashing display to be yellow/red, while the Traffic Control Devices Handbook and AASHTO Green Book caution that flashing yellow/red may be inappropriate and hazardous if sight distance is lacking or if traffic volume on the major street is moderate or heavy.

The study reported that informal surveys of engineering agencies in the Atlanta metro area resulted in a wide variety of interpretations of the MUTCD. Some engineers understood yellow/red to be the only acceptable form of flashing while others understood the MUTCD to mean that red/red is only acceptable where two major streets cross. Engineering judgment was primarily cited in selection of the flashing mode, with none of the agencies considering availability of minor street gaps in the selection of yellow/red versus red/red operation. Seven of the eight agencies surveyed judged that flashing red/red would produce intolerable congestion and all agencies agreed that flashing red/red should not be selected just because at some time of day, major street traffic could cause difficulty to vehicles entering from the minor street.

The study concluded that "If major-street volumes are too heavy for minor street traffic to enter or cross, or if sight distance for minor street traffic hinders safety, there appears to be no acceptable mode of flashing operation."

2.2 Findings of Previous Research on Flashing Signal Operations

The literature suggests that the selection of the flash mode (i.e. yellow/red or red/red) at a signal is primarily centered on the impact of flashing signals on vehicular delay. Operational analysis for low-volume late night/early morning program flash suggests that yellow/red flash should produce the lowest delay, provided that vehicular volumes are small (less than 200 vehicles per hour on the major approaches). However, it is unclear from the literature how a flashing signal performs from both an operational and safety perspective under medium and high traffic volumes.

2.2.1 Selection of the Mode of Flashing Operation

Throughout much of the U.S. the default mode of operation for signals in malfunction is flashing yellow on the major approaches with flashing red on the conflicting minor approaches. Flashing red on all approaches is typically reserved for special circumstances, where crash history dictates that flashing red on all approaches would improve safety. In many cases this default policy is not actually a formal written policy, instead it is considered a best practice based upon guidance from documents such as the Manual on Uniform Traffic Control Devices (MUTCD). The 2003 Edition of the MUTCD provides the following guidance on the application of flashing signal indications [7]:

> "When a traffic control signal is operated in the flashing mode, a flashing yellow signal indication should be used for the major street and a flashing red signal indication should be used for the other approaches unless flashing red signal indications are used on all approaches".

The 1995 ITE Journal article, based on the 1993 TTI study, stated the decision to use yellow/red or red/red flash should be based upon the delay and accident impacts [5].

The article continues that yellow/red flash produced the least delay (based upon study findings for low volume applications) but that accident rates tended to increase as the major street/minor street volume ratio decreases. Yellow/red flash should be utilized if the volume ratio is three or more (unless adequate sight distance is available), and red/red flash should be considered for volume ratios of less than three. Flash modes should be consistent for program flash or when the conflict monitor initiates flash mode. When initiated by the conflict monitor, it may also be desirable to select red/red flash due to the safety factor it provides to maintenance personnel.

The 1980 Federal Highway Administration study addresses the issue of mode of flashing operation and suggested a possible solution to utilize a national standard for flashing operation, but was hesitant to limit the flexibility of local engineers [3]:

> "A reasonable solution seems to be to specify as the national standard just one mode of flashing operation and to prohibit the other mode. This approach, however, may be too stringent to allow sufficient flexibility. So a corollary question becomes: If one mode of flashing were to be the rule and the other the exception – and it should be a rare exception – which mode should be which? Based on the above discussion, it would seem that having the yellow/red flash as the predominant mode would be better since drivers facing the flashing red would learn to expect that the cross street traffic would not be stopping; in the occasional situations where all-red flashing is needed, the violation of driver expectancy would not lead to a hazardous situation. If all-red flashing were the rule, however, an occasional exception could be quite dangerous."

The TTI study [4] provided the following recommendations for selection of the mode for flashing operation:

- Yellow/red flashing operation should be considered if the volume ratio is three or more unless adequate sight distance is not available
- Red/red flashing operation should be considered if either of the following conditions exist:

    - The volume ratio is less than three.
    - Adequate sight distance is not available.
- Emergency flashing operation (malfunction flash) should use the same mode of flashing operation that is used for the other types of flashing at the same intersection.
- The expected response time of police and maintenance personnel should be considered in the selection of red/red flashing operation. If queues and delays during the expected response time would exceed an acceptable level, consideration should be given to the use of yellow/red flashing operation.
- In some cases, it may be desirable to select red/red flashing operation for emergency flashing operation, due to the safety factor which it provides to maintenance personnel.

Based upon their recommendations, the TTI study identifies that red/red flash may provide some safety benefits over yellow/red flash. However, when providing recommendations on the selection of flashing mode, expected delay is a primary consideration. The study assumes in their recommendation for yellow/red flash at malfunctioning signals that queuing and delay would be lower than if red/red flash is provided. This assumption is based upon operations analysis for low volume conditions and is not validated for medium to high volume conditions that could be present at a signal operating in malfunction flash.

2.2.2 Driver Perception/Comprehension of Traffic Signal Displays

Although flashing signals seem to be a fairly straightforward concept, past studies have indicated that drivers may either fail to understand the signal indication, or misinterpret how other drivers at the signal will react. According to the Georgia State Code, a flashing signal has the following meaning [2]:

> **Flashing Red (Stop Signal)** – When a red lens is illuminated with rapid intermittent flashes, drivers of vehicles shall stop at a clearly marked stop line or, if there is no stop line, before entering the crosswalk on the near side of the intersection or, if there is no crosswalk, at the point nearest the intersecting roadways where the driver has a view of approaching traffic on the intersecting roadway before entering the intersection, and the right to proceed shall be subject to the rules applicable after making a stop at a stop sign.
>
> **Flashing Yellow (Caution Sign)** – When a yellow lens is illuminated with rapid intermittent flashes, drivers of vehicles may proceed through the intersection or past such signal only with caution.

To clarify interpretation of the state law, the Georgia Department of Transportation issued a set of instructions for proper driving through flashing traffic lights. The instructions mentioned the various reasons that a signal may operate in flash and recognized that different regions of the country or other parts of the world may have a different standard or interpretation which can lead to confusion or accidents. The following are the specific instructions to drivers on the interpretation of traffic signal indications in Georgia [8]:

> **At intersections where one direction has a flashing yellow light, and the other direction has a flashing red light:** Drivers who have a flashing yellow light do not have to stop. They should proceed cautiously through the intersection. Drivers who have the red flashing light MUST STOP. They should only pass through the intersection when it is safe to cross. They should not force their way into the intersection and challenge the cross-traffic to stop. In a busy intersection it may take a while for a gap to develop. Be patient.
>
> **At intersections where both directions have a flashing red light:** All drivers approaching this type of flashing signal MUST STOP. Then, the intersection should be treated like a four-way stop, with each leg of the intersection taking a turn to proceed. When there are multiple lanes, it is ok for two (or more) cars side-by-side to go at the same time. It is NOT OK to piggyback across the intersection with the car (or cars) in front of you, though.

> **At intersections where the traffic signal is totally dark – such as during a power failure:** When approaching an intersection where traffic lights are completely out, all traffic MUST STOP. Treat the light as if it was flashing red in all directions. Do not drive through the intersection as if a signal was not there. This is very dangerous, especially if someone in the crossing direction does the same thing.

These instructions suggest that there are recognized issues with driver actions and perception at signals operating in flash mode. Issues such as vehicle forcing their way into the intersection, vehicles stopping on yellow, vehicles failing to stop and instead entering the intersection by "piggybacking" onto the vehicle in front of it, and failing to stop when a signal is dark. Each of these actions (except for stopping on yellow) is a violation of state law and increases the potential for vehicle crashes. While stopping on yellow is not a violation, it violates driver expectancy as other drivers may not be anticipating the vehicle to stop, resulting in an increased potential for rear end crashes.

Although not likely the root cause of confusion, drivers in Atlanta seem to be getting some mixed instruction on how to navigate flashing signals. A 2004 public alert [9] issued by Mayor Shirley Franklin misquoted Georgia code in emphasizing in bold text, "It is important to treat intersections with malfunctioning lights as four way stop signs." It goes on to describe treating inoperative traffic lights as stop signs and provides a passing mention that if a flashing indication is given, the driver shall stop for a red indication and exhibit caution while passing through a yellow indication. While the correct information is technically given in the news brief, the manner in which it is presented is confusing to readers who would be likely to walk away from the document with the impression that a stop is required at all malfunctioning signals.

The 1993 TTI study summarized two previous projects that evaluated driver comprehension of flashing indications: the 1980 FHWA study [3] and another study by TTI specifically on the subject of driver comprehension of traffic control devices [10]. In both studies, drivers had a high understanding of the meaning of the flashing indication they were facing. Although, the TTI study did find that 10 percent of drivers facing a yellow light felt the indication meant stop before entering the intersection. The level of driver understanding significantly decreased when they were asked what indication the intersecting traffic would see.

Table 2.1 Driver Comprehension of Flashing Signals [4]

Question: If you are facing a flashing red signal, what will the cross-street traffic do?		
Response	FHWA Study [3]	TTI Study [10]
Slow	39.4 %	13.8 %
Stop	27.8 %	41.0%
Cannot Tell	32.9 %	41.1 %
Not Sure	--	4.1 %
Number of Respondents	353	1,745

The City of Lincoln, Nebraska studied [11] the state of practice for late night traffic signal operation as part of a traffic study. One of the reports recommendations was that flashing operation should only be reserved for intersection malfunction (flashing red for all approaches) or emergency vehicle preemption (if feasible). The study also presented the following observations:

1. A motorist facing a flashing red display may assume the opposing traffic signal to also display a flashing red, although a flashing yellow could be displayed.

2. Due to possible incorrect driver perception, it is not recommended that intersections operate with yellow/red operation. If flashing operation is implemented, red/red operation should be deployed.

2.2.3 Traffic Operations at Flashing Signals

Much of the flashing operation research is related to crash experience and safety. Only the previously mentioned FHWA [3] and TTI [4] studies were found to actually document traffic operations. The study undertaken by FHWA based its operational analysis on field data collected from 94 signals nationwide. The TTI study based its evaluation of delay on simulation model runs. While both studies offer conclusions and recommendations for flashing signal operation, both studies are also relevant to only the low volume conditions typical of program flash. The FHWA study notes that the identified conclusions "are based on averages found from the field data and that actual results for specific locations will vary. Furthermore, the results apply only to low volume levels where mean delay and proportion stopping are relatively unaffected by volume levels."

The FHWA study arrived at several conclusions regarding vehicle delay characteristics at flashing signal under low traffic volumes. These conclusions are based upon field data where two-way major street traffic was below 400 vph, with the majority of intersections at a rate of below 200 vph. The basis for the conclusions was a comparison of flashing operation to regular operation under late-night conditions.

- Flashing yellow/red produces less delay than any form of regular operation under all combinations of main and side street volumes.

- Flashing red/red produces less delay than pre-timed control under all volume combinations, even where signals are coordinated on an arterial or in a network.
- Flashing red/red produces more delay than fully actuated or semi-actuated, isolated control at all volume levels.

Within the FHWA analysis, an assumption was made that all vehicles at a flashing red signal stop, while no vehicles stop at a flashing yellow indication. However, this assumption runs contrary to the description of driver characteristics listed in the methods section for the stopped time delay study. Here, notes were made that "it is clear that drivers have a great aversion to coming to a complete stop..." Violations rates as high as six per hundred vehicles were documented in the report for vehicles failing to stop on a flashing red indication.

The study by TTI [4] evaluated the effect of a variety of geometric and volume combinations on traffic operations at flashing signals. Operational analysis was conducted using two simulation software packages: the TEXAS model and NETSIM. Again, this study was conducted with the intent of evaluating low-volume conditions suitable for program flash, to identify whether or not flashing operation is suitable from an operational standpoint for late-night/early morning conditions. The study arrived at the following conclusions:

- The study conclusions verified those arrived at by the FHWA study related to the delay characteristics for yellow/red and red/red flashing modes.
- The inference that can be drawn from the analysis is that yellow/red flashing operation should be used whenever possible, with few exceptions. A volume ratio

of about three is appropriate for changing to yellow/red flash operation (for late night/early morning program flash).

- Red/red and yellow/red flashing operation generally produce less delay than normal operation for traffic volumes under 450 vph per approach. For traffic volumes greater than 500 vph per approach, both modes of flash will produce as much or more delay as most normal signal operations.
- The decision to use yellow/red or red/red flash should be based on the delay and accident impacts. Analysis indicated that yellow/red flashing is most effective when the volume ratio is three or more. At ratios below three, red/red flashing operation results in lower delay.

2.2.4 Driver Behavior at Flashing Signals

Both the FHWA [3] and TTI [4] studies provide research results on driver behavior at flashing signals during late-night/early morning hours. The FHWA study evaluated violations per hundred vehicles for both normal and flashing operation. The study results are provided in Table 2.2. The study found that for locations where twenty-four hour normal operation was changed to nighttime yellow/red flash, the instances of violations increased for the minor street (facing a flashing red indication) and decreased slightly for the major street (facing a flashing yellow indication). Meanwhile, the conversion of late night operation to red/red flash resulted in the largest number of violations than with either alternative.

A violation was defined in the FHWA study as a vehicle not making a stop at a flashing red signal. The study assumed that vehicles that did not make a complete stop but reduced speed to a slow roll, were considered stopped and therefore not classified as a violator. The study indicates that it is impossible to violate a flashing yellow light, and therefore no violations were recorded for this condition. The data represents a half-hour of observation time per intersection for each condition, regular signal operation and flashing operation

Table 2.2 Violations Per Hundred Vehicles of Flashing Study Locations [3]

Street	Condition	Change in Control Regular to Yellow/Red Flash	 Regular to Red/Red Flash	 Yellow/Red Flash to Red/Red Flash
Major Street	Regular Flashing	1 0	2 5	0 3
Minor Street	Regular Flashing	1 6	2 3	1 4
Both Streets	Regular Flashing	1 1	2 4	1 3
No. of Intersections		81	6	2

Notes: (1) Normal operation indicates a "before" conditions with 24-hour normal signal operation
(2) Flashing indicates an "after" condition with implementation of nighttime flash.
(3) Data represents 1 hour of nighttime observation per intersection, per condition.
(4) For Yellow/Red to Red/Red conversions, the normal condition represents the original yellow/red flash operation.

The TTI study [4] documented seven intersections, filming activity from midnight to 6:00 am. The seven intersections comprised two yellow/red flashing signals, one red/red flashing signal, two pre-timed signals, and two actuated signals. Based upon observation of the video data, the study found that drivers at the pre-timed and actuated signal treated them as stop controlled intersections, stopping on a steady red and then proceeding into the intersection before the intersection changes to green. At flashing signals, drivers generally failed to completely stop on red indications and would make stops on a flashing yellow indication. Table 2.3 provides the results of the TTI study.

Table 2.3 TTI Driver Behavior Study [4]

Signal Operation	Street	Violations/100 Vehicles: Bryan/College Station Location	Violations/100 Vehicles: Bay City/Wharton Locations
Pretimed	Major	1.9	5.98
	Minor	2.4	1.32
Yellow/Red Flash	Major	1.8	0.68
	Minor	0.1	6.00
Red/Red Flash	Major	NA	2.33
	Minor	NA	6.15
Actuated	Major	1.8	0.72
	Minor	0.0	12.30

The TTI study results show a great deal of variability between the locations for each control type, although violations were identified for each type. The findings show that during low volume nighttime conditions, drivers were consistently failing to stop at red indications (both flashing and steady). While recognizing this potential safety concern, the TTI study inferred that the impact of these violations on safety was not serious due to the extremely low volumes present during nighttime conditions.

2.2.5 Studies on Accident Impacts of Flashing Signal Operations

Studies regarding accident experiences at signals under program flash comprise the body of the safety data available for flashing signals. Numerous safety studies have been conducted on the topic of program flash while no such studies were found to identify crash experience for malfunctioning signals. Several studies have associated crashes with the ratio of major street traffic volumes to minor street traffic volumes. The literature identifies significant variability in the accident rates for the different volume ratios. The literature review conducted as part of the TTI study [4] identified conflicting conclusions in prior studies, such as a study from Portland, Oregon concluding flashing operation was safer when the volume ratio was less than two, while an Oakland County

Michigan study identifying safer operation for a ratio greater than four. Based upon these findings, the TTI study suggests that conclusions drawn in previous studies related to volume ratio be used with caution.

Polanis [12] studied the changes in right-angle crash activity at 19 intersections before and after traffic signals were removed from programmed late-night/early-morning flash. Reductions in right angle crashes ranged from 29 percent to 100 percent. When aggregated, the reduction in right angle crashes measured 78 percent.

A 1987 study from Oakland County, Michigan, documented in two ITE Journal articles [13] and [14] was conducted to evaluate the relative accident impacts of flashing signal operation and stop-and-go signal operation during off-peak nighttime hours. The results of the study indicate that right angle accidents are significantly overrepresented at four legged arterial intersections when signals are in flashing mode during nighttime hours. T-type intersections and arterial collector intersections, where signals flash part time, experienced significantly fewer right-angle accidents than the other intersection types analyzed. Arterial intersections with nighttime hourly volume ratios of 2:1 or less have a significantly greater number of right-angle crashes than those with volume ratios of 4:1 or greater.

The Oakland County study, designed to update and validate a preliminary study conducted in 1983, analyzed accident data at intersections for the "before" period which had flashing signal operation at nighttime, and "after" period which had 24 hour full cycle signal operations. A total of 59 intersections were chosen by the Oakland County (Michigan) Road Commission for this study. Each of these signals was part of a group of 60 intersections that had been changed to 24-hour full cycle operation based upon the findings of the initial 1983 study and therefore provided three years of before and after data for examination. This study reconfirmed earlier findings that removal of flashing operation reduced right angle crashes and personal injury right-angle collisions at four-legged intersections of two arterial roadways. However, the frequency of rear-end accidents was not affected by the removal of flashing operation. The study recommended that consideration should be given to eliminating flashing operation if volume ratios are 4:1 or less. Consideration should also be given to eliminating flashing operation prior to 3:00 am, a time that corresponds with one hour past bars. This recommendation identifies that flashing operation may only be appropriate during the periods of the day when traffic volumes are at their lowest levels, with very low vehicle exposure to multiple vehicle crashes.

2.3 Causes of Signal Malfunction Flash

There are several ways a signal could enter into malfunction flash, including a loss of power to the cabinet, electrical power surges, or when initiated by the conflict monitor. The conflict monitor is a solid-state switch that induces flashing operation when it detects a potential conflict. The term conflict is somewhat misleading, as advancements in the industry has increased the number of "faults" [6]. In 1992, Parsonson and Walker identified that this safety-oriented trend could mean that malfunction flash could remain a frequent occurrence due to the ever increasing list of faults that could trip the conflict monitor. The following is a list of potential sources that may trip conflict monitor, as identified in NCHRP 166 [15]:

1. *Channel to Channel Conflict Detection:* Monitors protect against the display of greens, yellows, or WALK on conflicting movements. To define which movements are conflicting, the monitors assign a channel to each movement; the monitor can then be programmed to identify which combinations of channels can safely be displayed in the field.
2. *"Absence of Red" Monitoring:* Standard on NEMA monitors and available as an option from the manufacturers of Type 170 monitors, is the "absence of red" monitor function. The term is really a misnomer, because the monitor is actually checking for the absence of a display output on any one channel by monitoring the voltages on each channel's inputs. The function's logic is that if a green is not on, and yellow is not on, then red should be on. If not, a problem is assumed and the intersection is placed into the flashing mode. It should be emphasized that this feature does not protect against the absence of a red indication on a movement caused by burned-out bulbs or broken signal wiring. The monitor is checking for a voltage output from the load switches, and is not determining if the current is being drawn on the circuit – the only way to determine if bulbs are being illuminated.
3. *Controller Unit Voltage and Line Voltage Monitoring:* Conflict monitors can also check for proper voltage levels within the cabinet and controller unit. Both controller systems use a 24-volt DC power supply to operate auxiliary devices such as the load switches and detector inputs. The monitors can observe these voltage levels, and if the levels fall below the below a specified threshold, place

the intersection into flash until appropriate voltage levels are resumed. The conflict monitor also monitors itself for proper supply voltages.

4. *Controller Watchdog Monitoring:* Microprocessor-based controller equipment may occasionally experience a "stall" condition in which the microprocessor loses track of its place in the program and stops. This is usually in response to electrical interferences (nearby lightning is a primary cause) or, rarely, to a software error. To protect against this the, controller hardware and software designers use a "watchdog timer" circuit. The running program resets a memory address at regular intervals, typically about 10 times a second. A hardware timer circuit observes this memory address, and if the proper resetting is not occurring, the watch dog identifies an error condition.
5. *Intrachannel Conflicts:* Monitors conforming solely to NEMA standards or Type 170 specifications check only for conflicts between non-compatible channels; they do not check for intrachannel conflict conditions, such as green-yellow, green-red and yellow-red combinations within the same signal face. These combinations appear when an electric short occurs between the green and yellow outputs, or when a red load switch module fails "on". Most manufacturers offer conflict monitors with optional features to protect against some or all of these intrachannel combinations; these features are in addition to the requirements of the appropriate standards or specifications. Many agencies are opting for this added protection.
6. *Short-Yellow Monitoring:* Several manufacturers of conflict monitors are offering an optional feature that protects against skipping or displaying a too-short yellow

interval. This function requires that a minimum yellow (2.5 to 3.0 seconds) be displayed in every change from a green to a red on a channel. The current NEMA standards call for a controller unit to be capable of timing a yellow interval in the range 0 to 7 sec.

7. *Burned-out-Bulb Protection:* As mentioned earlier, the standard conflict monitor does not protect against the lack of an indication caused by burned-out red bulbs. Neither will it directly protect against burned-out yellow or green indications – the monitor only observes voltage levels and not the current draw, which is an indicator of circuit completion through a bulb filament. However, the standard monitor will trigger and indicate a channel to channel conflict error message if all yellow, green or WALK bulbs on a channel burn out. This is caused by a quirk in the design of solid state load switches, and is frequently a problem where single display heads are used, such as on left turn phase display. Many agencies require a loading resistor be installed on all single-display greens to avoid placing the intersection into flash for its non-critical condition.

Aside from the signal conflicts tracked by the conflict monitor, there are several other sources that frequently cause a signal to enter malfunction flash mode. These sources include issues with the power supply and power surges from lightning or other sources. These possible causes of malfunction flash mode are discussed in sections 2.3.1 through 2.3.5.

2.3.1 Power Supply Inputs

The inputs from the electric utility's power lines are the most frequent source of damaging surges to the controller assembly. Even though a lightning strike may contact the utility's cables a mile away, surges that are potentially dangerous to the signal equipment can be transmitted over the utility's distribution system to the controller. Ideally, the power service neutral conductor should be connected directly to the cabinet ground, although in some jurisdictions this is prohibited. The power service hot conductor, and the neutral conductor (if ungrounded), should be routed through the appropriate surge-protection device immediately upon entering the signal cabinet.

2.3.2 Loop Detector Inputs

Loop detectors, embedded in the roadway, can act as large antennas, picking up surges through the ground during a nearby lightning strike. Protection devices designed for use with loop detector leads are available and have been used successfully without affecting detector performance.

2.3.3 Field and Signal Wiring

Load-switch outputs to the signal heads at the intersection provide another ingress point for damaging surges. The most common form of protection for these circuits is the use of a metal-oxide varistor (MOV) on each outgoing conductor.

Pedestrian push-button circuits also provide exposure to harmful surges, particularly in the NEMA controller where the controller unit's logic common output is directly tied to the push-button terminals. Surge-protection device manufacturers recommend the tying of logic common output directly to cabinet ground and routing pedestrian detector inputs through surge protection devices.

2.3.4 System Interconnect

A system-interconnect cable provides the last of the potential sources of surges harmful to the controller equipment. All cables will require protection; cables used for modem communication will require a different type of protector than those needed for an AC interconnect cable. A shielded cable will help to protect the interconnect facilities; the shield should be grounded on only one end of the cable where it enters the cabinet.

2.3.5 Lightning

Power surges from nearby lightning strikes are a key culprit from many instances where signals revert to malfunction flash mode. The power surge could enter the controller unit via many of the equipment sources already listed. The NCHRP Report 317 [16] gives a method of calculating the number of lightning flashes striking a given region per year. The total number of flashes to ground per year worked out to approximately 1,800 for the City of Atlanta traffic control system area in 1989. With almost 1,000 traffic controllers located within this area, the probability of a controller being affected by lightning was very high and the cost of protection could be justified.

Specific requirements are provided by most jurisdictions for grounding the signal to prevent issues with power surges. Other devices are available to provide additional protection to the signal equipment within the cabinet and to prevent the signal from entering malfunction flash mode. Section 2.4 describes these preventative measures.

2.4 Protection Against Over-voltage, Electrical Transient, and Lightning Protection

The electrical inputs and outputs of the controller assembly are subjected to accidental over-voltages (as may occur when exposed field conductors are contacted by electrical transmission lines), electrical transients (frequently caused by nearby motors or neon signs) or surges from nearby lightning strikes. Minor electrical transients are well protected against in both the NEMA controller assembly (in the controller unit itself) and the Type 170 assembly, through the use of isolation devices on various inputs. However the possibility of more powerful surges requires additional protection.

2.4.1 Grounding Requirements

The first step is to install a grounding system that brings the cabinet and other grounded facilities as close to “absolute ground” as possible . Key components include one or more properly installed ground rods, of sufficient length for the surrounding earth conditions, and the shortest grounding possible bonding connection between the ground rod, the cabinet and conduit system [15].

2.4.2 Surge-Protection Devices

These are designed to route harmful surges away from the incoming conductor and direct them to the grounding system. NCHRP 166 identifies that during normal conditions the protection device provides a high resistance to ground, so that the normal operation of the conductor is not affected. However when a surge arrives on the conductor, the protection device must quickly (in nanoseconds or less) activate, providing a low resistance to ground and routing the surge away from the equipment being protected.

Most surge protectors on the traffic-control market are hybrid devices, combining two or more different devices to provide protection across the spectrum of possible surges. Many protectors must be replaced occasionally, as degradation of the protection characteristics occurs after several surges.

2.5 Literature Review Summary

Despite the fact that every traffic signal must have an assigned mode of flashing operation (yellow/red or red/red), the research available with which to make this decision is limited. Two research studies, one by the FHWA [3] and the other by TTI [4], represent a substantial portion of the current knowledge base on flashing signals. However, these studies are limited in scope to nighttime conditions with traffic volumes below 400 vph for the combined major street volume. Several other studies quantified safety issues for nighttime flashing operation, however no studies were identified that evaluated flashing operations under the moderate to high flows typically experienced at intersections in malfunction flash situations during daytime hours.

Based upon a review of the available literature, the following list summarizes key points presented in this chapter from previous studies on nighttime flashing operation:

- Drivers facing a red flashing indication have a low level of understanding of whether the conflicting cross street has a flashing yellow or flashing red indication.
- Results of field studies showed a significant increase in accidents when operating a signal in flash mode instead of normal (green-yellow-red) operation during nighttime conditions. The exception appears to be for very low volume conditions where the major street volume is less than 200 vph.
- The TTI study noted that there is no clear advantage to using flashing operation instead of normal operation and any flashing operation implementation should require an engineering study prior to implementation.

- The yellow/red flash mode is interpreted by some engineers to be the only acceptable form of flashing operation, with delay being a primary consideration in the selection. Yellow/red flash is the more efficient mode because major street vehicles are not required to stop.
- Red/red flash should be considered where adequate sight distance is not available and is regarded as the safer mode since all vehicles must stop, however delays and congestion resulting from red/red operation may be undesirable.
- Below 450 vph both yellow/red and red/red flash operation produce less delay than normal operation. However above 500 vph, both modes of flash produce as much or more delay than most normal signal operations.
- A primary factor used to quantify thresholds for flashing operation and safety was the ratio of major street/minor street traffic volumes. However, these ratios vary between studies and may not be applicable to high volume scenarios.
- There appears to be recognized issues with violations and confusion among drivers at flashing signals. Both the FHWA and TTI study cited violations of failing to stop at a red indication as a potential safety concern.
- Signals may enter the malfunction flash mode for a variety of reasons, including a conflict within the signal equipment detected by the malfunction monitoring unit, or a power surge from lighting or other sources.

These findings highlight an uncertainty in actual signal operations for conditions outside of the low-volume nighttime scenario. They further indicate potential safety issues due to a lack of driver comprehension, violations of the flashing signal indications, and an increase in crashes for volume conditions above 200 vph. The following chapter identifies the methodology employed for measuring the performance of signals operating in malfunction flash mode under moderate to high volume traffic conditions. This includes procedures for data collection, reduction, and quality control, with results from the analysis provided in subsequent chapters of this report.

CHAPTER 3

FIELD TESTS OF MALFUNCTION FLASH OPERATION

As seen in Chapter 2, two major studies are generally cited as support for current mode of flashing signal operation guidelines, the 1980 FHWA *A Study of Clearance Intervals, Flashing Operation, and Left-turn Phasing at Traffic Signals: Volume 3 Flashing Operation* [3] and the 1993 Texas Transportation Institute (TTI) *Evaluation of Flashing Traffic Signal Operation* [4]. The 1980 FHWA study utilized field data to analyze delay, vehicle conflicts, and violations of the traffic signal display when in flashing operation. The vehicle demands included in the FHWA field data ranged from approximately 5 to 400 vehicles per hour for both directions of travel along the major roadway, relatively low volume demands, consistent with what would be expected during the late night to early morning hours. The TTI study was primarily based on the assumption that an intersection would have traffic performance characteristics similar to a two-way stopped controlled intersection when flashing in yellow/red and an all-way stop controlled intersection when flashing in red/red. Analysis was conducted for a range of volumes using the operational models and simulation tools of the day for the respective unsignalized intersection type.

The FHWA and TTI studies generally agreed that under low volume conditions yellow/red was preferred over red/red flashing operation, providing lower delays while maintaining traffic flow. Although both studies hinted at potential safety issues at higher traffic volumes, neither study specifically obtained field data for flashing signals at higher traffic volumes. By concentrating on low volume nighttime conditions neither study directly captured the operational characteristics likely to be experienced when a signal goes into malfunction flash during higher demand daytime hours, particularly during the morning and evening peak periods.

In order to get an accurate understanding of driver behavior and evaluate the potential intersection traffic operational affects of malfunction flash signal control it is necessary to collect data while an intersection is experiencing typical daytime traffic demands. This data may then be used to identify operational differences under flashing control, if any, which may be present between low volume nighttime demands and higher daytime demands.

3.1 Data Collection

A signal operating in malfunction flash is an unexpected and uncommon event for motorists and, as such, their response is uncertain. To accurately understand traffic operations at a flashing signal it is important to collect data at actual intersections while in flash mode. However, intentionally placing a functioning signal in malfunction flash would introduce unnecessary and unacceptable safety risks. Therefore, this study is unable to incorporate a structured data collection plan where study intersections and traffic demands may be pre-selected. Rather, data collection is limited to signals in actual malfunction flash resulting in a random sample of intersections and demands.

To collect data for a randomly occurring event, several students and faculty were recruited to continuously carry video cameras in their vehicles in order to capture data at any encountered signal operating in malfunction flash. Radio and news websites were also monitored to identify locations with signals operating in malfunction flash.

3.1.1 Data Collection Procedure

Due to the additional demands placed on motorists and additional conflicts present at a flashing traffic signal it is important that data collection efforts not distract motorists or otherwise interfere with traffic operations. To ensure this, the following procedure was developed for all persons involved with collecting data.

Upon arrival at a traffic signal operating in malfunction flash mode the data collector was instructed to:

1. Safely and legally park their vehicle outside of the area of the signalized intersection so as to not disrupt or influence traffic.
2. Report the malfunctioning signal to the agency that maintains the intersection currently in flash. (A list of contact numbers for local agencies was developed and provided to each data collector.) If the signal location is in a jurisdiction not listed, call 411 to obtain the phone number of the appropriate agency. If unable to determine what agency maintains a specific signal, or contact the responsible agency, call 911 and report the signal malfunction.
3. Set up the video camera to record intersection operations. The camera must be placed outside of the roadway or any other areas that would directly influence vehicular traffic. The camera should also be placed in a discreet location to minimize the likelihood of driver distraction. To collect the necessary data, the camera must be positioned so that all intersection approaches are recorded.
4. If it is not possible to set up the camera to meet the conditions in 3 then data is not to be collected at the intersection.

5. Film traffic at the intersection for up to 90 minutes or until a signal maintenance crew responds and returns the signal to normal operation.
6. Return the video cassette tape to the lab. Label the location, time, and date on the tape and tape case. Also note the intersection lane configurations and other geometric features including potential sight distance limitations on the approaches.

At all times the safety of the traveling public and the data collector are of primary importance and the collection of the actual data is treated as secondary.

3.1.2 Study Intersections

Data was collected at 13 intersections in and around metro Atlanta, Georgia, between May 2005 and January 2006. Eleven signals operated in yellow/red flash mode, while the remaining two intersections operated in red/red flash mode. Table 3.1 lists the study locations and summarizes their basic characteristics. Aerial photographs for each of the study intersections is provided in Appendix A. That data is primarily recorded in the Atlanta area should not be taken as a reflection of the quality of signal maintenance in this region. Data collection is primarily limited to areas within the travel patterns of the data collectors, which tended to concentrate near the Georgia Tech area.

Most locations were filmed during daylight hours and during dry conditions. Data was collected primarily during daylight hours as the method of identifying flashing signals typically involved randomly happening upon a signal in flash or relying on friends for alerts to locations. Due to travel patterns of the people involved in the study, few night locations were recorded. Even where nighttime flashing occurred it is often difficult to find a satisfactory video set-up location, as headlight glare becomes a large problem. Also, data collectors are advised against filming during thunderstorms, as lighting and heavy rain present unwarranted safety risks. Thus, for intersections where the signal enters malfunction flash during a thunderstorm data is collected only once the storm passes.

Table 3.1 Study Locations and Characteristics

	Location Name	**Date [Start Time]**	**Length of Video Data (minute)**	**Mode of Flash**	**Light Condition**	**# of legs**	**# of Major St. legs [# lanes per approach]***	**# of Minor St. legs [# Lanes per approach]***
Malfunction Yellow/Red Flash	Northside Dr. at Peachtree Battle Ave.	5/11/2005 [9:00 AM]	62	Yellow/ Red	Daylight	4	2 [2]	2 [2]
	Monroe Dr. at 10th St.	8/17/2005 [4:50 PM]	45	Yellow/ Red	Daylight	3	2 [2]	1 [3]
	Rainbow St. at Candler Dr.	8/12/2005 [3:05 PM]	24	Yellow/ Red	Daylight	4	2 [4 and 3]	2 [2]
	N. Highland Ave. at University Dr.	9/21/2005 [8:25 AM]	61	Yellow/ Red	Daylight	3	2 [1]	1 [2]
	Lenox Rd. at Phipps Blvd.	9/30/2005 [9:25 PM]	52	Yellow/ Red	Dark / Streetlights	4	2 [6 and 5]	2 [4 and 3]
	Spring St. at 17th St.	10/15/2005 [10:55 AM]	91	Yellow/ Red	Daylight	3	1 [4]	2 [3 and 2]
	W. Peachtree St. at 11th St.	10/15/2005 [1:05 PM]	85	Yellow/ Red	Daylight	2	1 [4]	1 [1]
	W. Peachtree St. at 16th St.	10/22/2005 [3:30 PM]	61	Yellow/ Red	Daylight	2	1 [4]	1 [1]
	14th St. at Williams St.	10/22/2005 [1:20 PM]	61	Yellow/ Red	Daylight	3	2 [3 and 2]	1 [3]
New Signal Yellow/Red	Market St at 16th St.	10/26/2005 [2:30 PM]	62	Yellow/ Red	Daylight	3	2 [2]	1 [1]
	17th St. at Bishop St.	9/26/2005 [5:00 PM]	46	Yellow/ Red	Daylight	3	2 [4 and 3]	1 [2]
Malfunction Red/Red Flash	Piedmont Rd. at The Prado	11/15/2005 [5:35 PM]	53	Red/Red	Dusk to Dark / Streetlights	4	2 [3]	2 [2 and 1]
	Roswell Rd.at W. Wieuca Rd.	1/14/2006 [11:20 AM]	62	Red/Red	Daylight	4	2 [3]	2 [2]

* Where the number of lanes varies for a street with two approach legs, [X and Y] indicates the number of lanes for each approach X and Y individually.

3.2 Video Data Reduction

To analyze the operational effects of malfunction flash individual driver and driver interactions are manually recorded from the video. A Microsoft Excel based Visual Basic program was developed to aid in video data reduction. The developed program effectively utilized the computer keyboard as a data collection board, with each keystroke storing data for a particular vehicle action, similar to that of commercial data collection instruments (e.g. Jamar traffic data collection boards).

Initial versions of the program were fairly simplistic. While replaying the video an individual would attempt to observe all intersection approaches simultaneously, recording the time each vehicle entered the intersection. After the data is recorded a second person would compare the recorded time stamps with random sections of the video to ensure data quality. This data reduction procedure was initially thought to be sufficient to quantify vehicle behavior. However, during several iterations in the reduction of the first few videos, several issues were identified:

- A high percentage of vehicles on the roadway approaches with a flashing yellow indication stopped. The initial data collection procedure did not allow for distinguishing between those vehicles that stopped and those that did not.
- The initial data collection procedure did not distinguish between single-lane and multiple-lane approaches. To identify individual vehicle behavior (e.g. headways between departing vehicles) lane-by-lane data reduction would be required.
- Vehicles often traversed the intersection as part of a platoon, including on those approaches with flashing red indications. When a platoon traversed the intersection on a flashing red approach only the lead vehicle stopped. As with the

flashing yellow approaches the initial data collection procedure did not allow for distinguishing between those vehicles that stopped and those that did not.

- When reducing vehicle data, only one approach or a portion of an approach could be reduced with reasonable accuracy at one time. Attempting to observe all approaches simultaneously resulted in poor data accuracy.

Based on the initial data reduction efforts it was determined that the data reduction must be on a lane-by-lane basis, one approach at a time. Also, that for each vehicle the time the vehicle stopped and departed from the stop bar (for vehicles that did not stop only a departure time is recorded) and the vehicle direction of departure (left, thru, or right) should be recorded. Another desirable data element that unfortunately is not able to be collected is the time a vehicle first entered a queue. Do to the limitation in available camera angles at each intersection it is not possible to reliably capture the back of queue on the video recordings.

Once the individual vehicle data is reduced from a video it is then aggregated by time (e.g. 1 min, 5 min, etc. bins), turning movement, lane, approach, etc. as part of the intersection analysis. Additionally, as the data for each vehicle is recorded, additional notes are taken to identify times and details of incidents or "near-misses" that may later be referred to and evaluated. The analysis of the data is presented in Chapter 4.

3.2.1 Data Reduction Procedures

Due to the labor-intensive nature of the data reduction, several people were employed to reduce the data in a timely manner. To ensure consistency in the data reduction, a procedure was implemented that centered on the developed Excel based data reduction program. An Excel workbook was created for each video based on a clean version of the developed Excel program. Each workbook had separate worksheets for reducing each of the intersection approaches (up to 4 approaches) and allowed for up to 4 lanes per approach.

Figure 3.1 shows an example of the data reduction form for a single approach. Note that Figure 3.1 identifies that this form is to be used for the major street traffic traveling away from the camera. It was determined that data accuracy could be improved by creating separate input procedures for vehicles traveling away from the camera and toward the camera. In the initial efforts where separate procedures were not used there was a significantly lower data collection accuracy when vehicles were traveling toward the camera. This was due to the fact that left turning vehicles appear on the right side of the road when viewed on the screen. Thus to improve accuracy, two sets of keyboard set-ups were established depending on whether vehicles were traveling toward or away from the camera.

Approach Name Piedmont Road
Direction (NB, SB, EB, WB): SB

Date: 2/18/06
Data Reduced By: Justin Bansen

Form Set-Up | Clear Form | Open Data Form

USE THIS FORM FOR THE *MAJOR STREET* TRAVELING ***AWAY*** FROM THE CAMERA

A	B	C	D	E	F	G	H	I	J	K
Program Function	Time	Elapsed Time	Lane 1 Stops	Lane 1 Left	Lane 2 Stops	Lane 2 Thru	Lane 3 Stops	Lane 3 Right or Thru	Lane 4 Not Used	Lane 4 Not Used
START	9:04:30	0:00:00								
	9:04:32	0:00:02			Stop					
	9:04:32	0:00:02					Stop			
	9:04:33	0:00:03				Depart Thru				
	9:04:33	0:00:03						Depart Thru		
	9:04:35	0:00:05			Stop					
	9:04:35	0:00:05					Stop			
	9:04:39	0:00:09				Depart Thru				
	9:04:40	0:00:10						Depart Thru		
	9:04:42	0:00:12			Stop					
	9:04:43	0:00:13					Stop			
	9:04:43	0:00:13						Depart Thru		
	9:04:44	0:00:14				Depart Thru				
	9:04:46	0:00:16			Stop					
	9:04:46	0:00:16					Stop			
	9:06:03	0:00:20						Depart Thru		
	9:06:05	0:00:22					Stop			
	9:06:05	0:00:22				Depart Thru				
	9:06:09	0:00:26						Depart Thru		
	9:06:13	0:00:30					Stop			
	9:06:14	0:00:31						Depart Thru		
	9:06:15	0:00:32			Stop					
	9:06:16	0:00:33				Depart Thru				
	9:06:24	0:00:41			Stop					
	9:06:26	0:00:43				Depart Thru				
	9:06:27	0:00:44					Stop			
	9:06:29	0:00:46						Depart Thru		
	9:06:31	0:00:48			Stop					
	9:06:31	0:00:48					Stop			
	9:06:32	0:00:49				Depart Thru				
	9:06:32	0:00:49						Depart Thru		
	9:06:58	0:01:15					Stop			
	9:07:02	0:01:19			Stop					
	9:07:03	0:01:20						Depart Thru		
	9:07:06	0:01:23					Stop			
	9:07:06	0:01:23				Depart Thru				
	9:07:08	0:01:25						Depart Thru		
	9:07:09	0:01:26			Stop					
	9:07:10	0:01:27						Depart Right		
	9:08:36	0:01:32					Stop			
	9:08:37	0:01:33				Depart Thru				

Figure 3.1 Sample Approach Form with Raw Reduced Data

For data reduction, the following procedure is utilized:

1. Open .mpg (video) file and Excel file and arrange them such that both are visible on screen. For ease of viewing the use of two computers is recommended. One computer is used for viewing the video on a full screen while the other computer can be used to run the video reduction program.
2. Select the appropriate worksheet for the approach that is to be reduced. Approaches with a flashing yellow display are always identified as the major

approaches. Two major street approaches are provided, one for vehicles traveling toward the camera and one for vehicles traveling away from the camera. The remaining minor street approaches use the worksheets titled “Minor 1” or “Minor 2”.

3. Select the “Form Set-Up” button at the top of the sheet. A dialog box opens that allows the user to select the appropriate lane configuration for the intersection approach being reduced. Figure 3.2 shows the “Form Set-Up” dialog that corresponds to the approach data sheet in Figure 3.1. Note that the label order (i.e. right | thru | left) matches the direction vehicles would be turning if they were traveling toward the camera. Additional configurations were added if the actual configuration was different from the options presented. The form set-up also dictates which keys (see Table 3.2) will be used in the analysis by assigning each movement to a specific lane on the sheet (Lane 1, 2, 3 or 4 shown in Figure 3.1).
4. Select the “Open Data Form” button in the Excel file to open a dialog box. This opens the controls (shown in Figure 3.3) for the Visual Basic program that records key presses. Pressing “Start” initiates the program. The pause and resume buttons allow the program to be suspended and then resumed at a later time. When all video data has been reduced, pressing the “End” button exits the Visual Basic program. Clicking the “Start” button will change the status window in Figure 3.3 to the color green with a status of *Running*. Clicking the “Pause” button will change the status to *Paused* with a yellow background color.

Figure 3.2 "Form Set-Up" Dialog Box

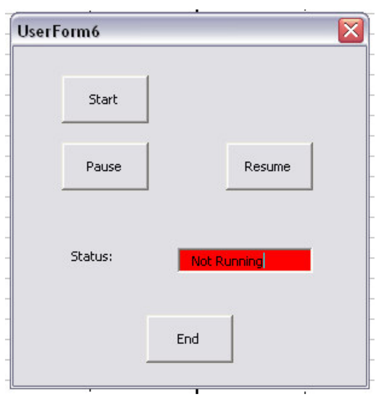


Figure 3.3 "Open Data Form" Control Dialog Box

5. Click the "Play" button on the video and the "Start" button in the control dialog box as near to simultaneous as possible to ensure that the time stamps being assigned by the Visual Basic program are in sync with the video. It is important to note that the recorded time stamp is not read from the video, instead it is based on the computer clock time. Thus, it is important that the video be played at real-time. For very light traffic it is possible to run the tape at faster than real-time (or

slower than real-time for heavy traffic), although the recorded time stamps must then be adjusted to account for the ratio between the computer clock and video play speed.

6. For each vehicle press the key that corresponds to the vehicle activity and lane. A list of key assignments is provided in Table 3.2.

Table 3.2 Keyboard Key Assignments

Keyboard Key	Vehicle Coming Towards	Vehicle Going Away
A	Lane 1 Depart Right	Lane 1 Depart Left
S	Lane 1 Stop	Lane 1 Stop
D	Lane 2 Depart Thru	Lane 2 Depart Thru
C	Lane 2 Depart Left	Lane 2 Depart Right
E	Lane 2 Depart Right	Lane 2 Depart Left
F	Lane 2 Stop	Lane 2 Stop
J	Lane 3 Stop	Lane 3 Stop
K	Lane 3 Depart Thru	Lane 3 Depart Thru
I	Lane 3 Depart Left	Lane 3 Depart Right
L	Lane 4 Stop	Lane 4 Stop
;	Lane 4 Depart Left	Lane 4 Depart Right
\	Undo Previous	Undo Previous

Keyboard key presses are differentiated by whether or not the vehicle is coming toward or away from the camera, as discussed previously. Each lane on the approach is assigned up to four keys, each representing one of four possible activities: stop, depart left, depart thru, or depart right. Each key press records the computer time stamp associated with that key's associated activity. For vehicles that do not stop a stop time is not recorded.

To ensure consistency between individuals collecting data a vehicle is recorded as having stopped only if it reaches a full stop for any amount of time (even if it was a stopped time was less than a second). Vehicles are not counted as being stopped if they slowed but did not come to a complete stop, or are previously stopped in the queue but followed the vehicle in front of them through the intersection. That is, to be counted as a stopped vehicle a vehicle must stop at the stop bar prior to entering the intersection (i.e. similar to the rules at a stop sign).

7. Once all vehicles within the video have been recorded, press “End” in the control dialog box to exit the program.
8. Repeat the data reduction procedure for each of the intersection approaches on the appropriate sheet.

3.2.2 - Quality Control for Data Reduction

As part of quality assurance and quality control, random sections of reduced video data are compared to the original video by a second person. The data is spot checked to verify that vehicle stop and departure times are accurately recorded and that vehicle stops are being interpreted consistently. Also, as each approach is analyzed separately, each is recorded relative to an independent time code. Therefore, the data from each approach required compiling into a single file (that is, the time codes are synchronized) to ensure that vehicles entering the intersection from different approaches entered in the same order as seen in the video. Listed below are some common errors found and measures taken to ensure quality of data:

1. **Vehicles or vehicle stops not recorded.** Typically a failure to capture a vehicle or a vehicle stop is due to either a large number of lanes or a high traffic volume. In either case, there is too much activity for the person reducing the data to capture all at once. Thus, data is collected again with the approach subdivided in two or three section, each analyzed independently. This error type most often occurs where there are four lanes of traffic or three lanes of consistently heavy traffic. It was found that when trying to capture individual stops and departures by movement (left, thru, or right) that a maximum of only two lanes could be reduced at one time while maintaining acceptable accuracy.
2. **Entire approach stops or departure times not in synch with the video.** A common finding in the reduced data is that all the data for a specific approach is a second or two out of synch with the video, which translates into the compiled data being out of sync as well. This phenomenon could be attributed to several factors, one of which being that the video tape and the Visual Basic data reduction program were not started simultaneously. Another cause could be that the person reducing the data was consistently late in depressing the appropriate keyboard key to log vehicle activity. This most often occurs where little of the upstream portion of the approach is visible within the video frame, making it difficult to anticipate vehicle activity due to the limited time period that a vehicle is within the frame prior to entering the intersection. To address this error each individual approach is evaluated and the activity time stamps uniformly adjusted as necessary, and the file recompiled. The recompiled data is then again evaluated against the video to

ensure that the adjusted data is recorded in the proper order for vehicles entering the intersection each approach.

3. **Vehicles or stops missed when large platoons of vehicles approached the intersection.** This problem is less common, but typically occurs for those signals with a nearby upstream signal. The data has extremely high flow periods (due to upstream green) followed by a low flow periods (due to upstream red). In this case, the low flow periods are usually extremely accurate, while the high flow periods overwhelm the person reducing the data. To ensure that all vehicles are accurately recorded, the video is reviewed and compared against the reduced data for the high flow periods, with any missed vehicle activity manually corrected rather than re-reducing the approach in it's entirety.

3.3 Summary of Study Methodology

Field data collected at signals operating in malfunction flash mode provide the basis for this study. Data is collected by responding to signals already in flash mode and the signal is videotaped for up to 90 minutes or until maintenance crews responded to the scene. Data was collected from 13 intersections in and around metro Atlanta, Georgia between May 2005 and January 2006. Video data was captured at 11 signals operating in yellow/red flash mode and two intersections in red/red flash mode. Locations were filmed primarily during daytime hours to capture moderate to high traffic volumes. Video data is reduced utilizing a program developed in Microsoft Excel Visual Basic. Data is reduced to capture the time of stopping and departure for each vehicle traversing the intersection, with vehicles identified by approach and by lane. Thus each vehicle is assigned a record of its activity, location, and turning maneuver to be used in later analysis.

Chapter 4 presents the results of the data analysis with respect to a number of characteristics including vehicle stopping behaviors, platooning characteristics, the impact of minor street vehicle presence and absence, and rates of signal violations.

CHAPTER 4

ANALYSIS AND FINDINGS

Analysis for quantifying the operations for flashing signals differs from that of traditional intersections. The Highway Capacity Manual provides no operational model for predicting operations at a flashing signal and similarly, there currently are no software packages specifically designed to analyze operations at a flashing signal. Thus, the undertaken evaluation of operations at a flashing signal relies on the analysis of field data collected while intersections are in flash mode (field data collection is discussed in Chapter 3). For the analysis, the Excel based data reduction program described in Chapter 3 is enhanced to summarize the collected raw data and run analysis sub-routines. Visual Basic scripts are utilized for compiling the raw data for each of the individual approaches and lanes and for performing the majority of the analysis.

As no standard flashing signal analysis procedure exists it is necessary as part of this effort to identify Measures of Effectiveness (MOE's) for quantifying the operational characteristics of flashing signals. Since flashing signals are an unexpected event, the operations analysis focuses upon driver behavior exhibited on the video taken at the study intersections. Analysis of driver behavior includes an evaluation of the tendency of vehicles to stop when presented with a flashing yellow or red indication, platooning effects for vehicles entering the intersection in groups by lane or by approach, and the extent to which the presence of minor street vehicles affects the behavior of major street traffic.

4.1 Analysis of Vehicle Stopping

During data reduction, there was visual evidence that vehicle stopping was erratic and did not follow the common expectation that vehicles facing a flashing red will stop and vehicles facing a flashing yellow will not stop, as indicated in the GDOT flashing signal driver guidance (see Section 2.2.2 in Chapter 2). Observation of the flashing signal intersection videos readily leads the viewer to suspect that flashing signals under typical daytime traffic conditions (as opposed to low volume night-time conditions typical of program flash) do not operate with the same characteristics as an unsignalized intersection, as assumed in many previous research projects including the 1980 FHWA study [3] and 1993 TTI study [4]. Should these observations prove to be correct it may be not be appropriate to assume that the intersection will function as an unsignalized intersection while in flash mode, nor appropriate to assume that a driver will treat a flashing signal the same as they would a two-way or four-way stop.

4.1.1 Discussion of Video Observations

The first task of the analysis was to review the video recordings to identify any unexpected or potentially unsafe driver behavior at flashing signals. Several recurring driver habits were observed that run contrary to the driver behavior typically expected of drivers at either a signal or a two-way stop controlled intersection, particularly regarding the likelihood of vehicles facing a flashing yellow signal indication (major street vehicles) yielding the right-of-way to vehicles facing a flashing red signal indication (minor street vehicles). The following are typical scenarios observed from the video recording that run counter to traditional assumptions of vehicle behavior at an unsignalized intersection.

1. There are often occasions at signals flashing yellow/red where vehicles on the major street stop on a yellow flashing indication and allow minor street vehicles (facing a red flashing indication) to enter the intersection. The flashing yellow display seems to create driver confusion that results in major street vehicles stopping to allow for minor street vehicles to enter the roadway.
2. Major street stops are not limited to just a courtesy stop to allow minor street vehicles to make their turn maneuver. Some major street vehicles were found to stop at a flashing yellow even in the absence of minor street vehicles.
3. At an intersection flashing yellow/red some minor street vehicles (facing a red flashing indication) will not wait for a gap in the major street traffic, instead they creep into the intersection until the major street stops. This same phenomenon is apparent at two-way stop intersections where minor street vehicles are faced with large conflicting major street volumes, resulting in high delays.
4. In many instances vehicles on the minor street may not be able to identify what color display is being given to the major street. Thus, the minor street vehicle begins to enter the intersection under the expectation that the major street vehicle is supposed to stop. This behavior has also been documented in the literature review where past studies have identified that the majority of drivers had difficulty identifying the actions of the cross street.
5. Some minor street vehicles (facing a red flashing indication) do not stop on red, but rather enter the intersection as a platooned vehicle following the lead vehicle in the group. Sometimes referred to as "piggybacking", this action was common for both the major and minor streets.

6. At high volumes, signals operating in flashing yellow/red mode, appeared to operate as a four-way stop, with nearly all vehicles stopping and then departing in an alternating fashion between the major and minor approaches.

Scenarios 1, 2, 3, and 5 are all examples of activities that the Georgia DOT identified for drivers NOT to do at flashing signals [8]. This suggests that these driver behaviors are ongoing issues, which persist despite the preparation of educational materials for the public. There are several potential reasons for this ongoing confusion, such as: a significant portion of the public is simply unaware of the proper methods for navigating an intersection in malfunction flash mode (in which case the literature has not been distributed broadly enough), drivers are ignoring the rules of road, or drivers are confused and misinterpreting the indication that is being given to the conflicting traffic stream. Each of these fall under traditional explanations that tend to seek driver errors or misunderstandings to explain hazardous behaviors. Of course, another possible reason for the ongoing confusion is that drivers are innately uncomfortable with the prescribed method for navigating a flashing signal when volumes at the intersection reach high levels and adequate control is not being provided.

For comparative purposes observations were also made at several two-way stop controlled intersections with permanent flashing beacons. These beacons typically are comprised of only one signal head per approach, flashing either yellow or red. Observations at these intersections did not find the same level of confusion that existed at intersections in malfunction flash. There are several potential reasons for the apparent lack of confusion. First, beacons are in constant flash, which generates a level of driver expectation, whereas signals in malfunction flash mode are an unexpected events for motorists. Also, beacons are only on low volume intersections (as at higher volumes the intersections would be signalized). As seen in previous literature, low volume intersections under flashing operations did not seem to create the same level of driver confusion.

4.1.2 Vehicle Stopping Analysis Results

Analysis was performed to identify the extent to which major street vehicles stopped on a yellow indication. Table 4.1 provides the percentage of all major street vehicles stopping as well as the percentage of only the major thru vehicles stopping. The percentage of thru vehicles stopping is thought to provides a better point of comparison between intersections since turning vehicles may have a higher tendency to stop, especially left turning vehicles, due to the presence of conflicting vehicles on the opposite major street approach.

As a point of comparison, raw volume counts for both the major and minor street are provided in Table 4.1. These volumes represent the entire length of the video recorded. Since the length of video data is different for each intersection, volume data is also provided as a peak hourly flow rate. Turning movement counts and other additional traffic volume data is provided in Appendix B.

Table 4.1 Major Street Stops on Flashing Yellow Indications

	Intersection Name	Video Length (minute)	Major volume (2-way)	Major Peak Flow Rate (veh/hr)	Minor Volume (2-way)	Minor Peak Flow Rate (veh/hr	% Major Stops – All Vehicles *[# Stops]*	% Major Stops – Thru Vehicles *[# Stops]*
Malfunction Yellow/Red Flash	Northside Dr. at Peachtree Battle Ave.	62	1029	1164	436	536	59.7 % *[614]*	58.6 % *[493]*
	Monroe Dr. at 10th St.	45	1099	1424	531	820	59.7 % *[656]*	57.8 % *[484]*
	Rainbow St. at Candler Dr.	23	711	1848	295	780	51.8 % *[368]*	57.9 % *[286]*
	N. Highland Ave. at University Dr.	61	919	1024	227	272	11.5 % *[106]*	9.8 % *[82]*
	Lenox Rd. at Phipps Blvd.	52	1631	1888	441	660	39.9 % *[650]*	32.9 % *[449]*
	Spring St. at 17th St.	90	883	704	1199	956	46.2 % *[408]*	45.4 % *[320]*
	W. Peachtree St. at 11th St.	85	1171	944	88	52	0.8 % *[9]*	0.7 % *[8]*
	W. Peachtree St. at 16th St.	61	1495	1680	212	212	10.6 % *[159]*	8.6 % *[120]*
	14th St. at Williams St.	60	1522	1600	888	928	57.2 % *[871]*	59.7 % *[727]*
New Signal Yellow/Red Flash	Market St at 16th St.	62	456	508	14	12	17.1 % *[78]*	16.5 % *[70]*
	17th St. at Bishop St.	46	608	844	214	384	7.9 % *[47]*	2.9 % *[14]*
Malfunction Red/Red Flash	Piedmont Rd. at The Prado	53	1918	2280	274	304	84.7 % *[1625]*	85.3 % *[1541]*
	Roswell Rd.at W Wieuca Rd.	63	1900	1852	740	784	83.5 % *[1586]*	83.6 % *[1342]*

Notes: (1) Peak flow rates are calculated based upon the vehicular volumes occurring during the peak 15-minutes (of the recorded data) for the entire intersection. Major and minor flow rates represent the volume occurring during the peak 15-minute period for the respective approaches, multiplied by four. Peak flow rates represent two-way traffic.
(2) Major and minor volumes represent the total volume in both directions of travel along a roadway over the entire duration of the video.
(3) *[# Stops]* in the rightmost two columns represents the raw number of vehicles stopping over the entire duration of the video.

4.1.3 Discussion of Findings for Yellow/Red Flash Operations

The vehicle stopping analysis, shown in Table 4.1, indicates a wide range in the percentages of vehicles stopping on a yellow indication. On the low end of the range, the lowest average rate of thru vehicles stopping was found to be 0.7 percent at the West Peachtree Street and 11th Street intersection. The major approach (W. Peachtree St.) of this intersection is a four-lane arterial street that is part of a one-way couplet. Vehicles on the major street typically arrive in platoons and move through the intersection in a mass, with subsequent vehicles behaving similarly to the vehicle ahead of it. During the time the video was captured the, minor street flow rate was only 52 vehicles per hour.

The highest average stopping rate was 59.7 percent, found for the intersection of 14th Street and Williams Street. Flow rates for this intersection were high for both the major and minor approaches to the intersection with minor street peak flow rates in excess of 900 vehicles per hour.

It is clear that the range of 0.7 percent to 59.7 percent stops implies a wide variation in traffic operations at different intersections and under different volume demands. However, in examining vehicle operations aggregated over an hour, much of the dynamic aspects of the traffic operations are lost. Observations of the video indicated considerable variability in operational and safety performance from minute-to-minute. Even at a single intersection over a relatively short time frame driver behavior and the resulting percentage of vehicles stopping on the major street are dynamic, changing in response to the prevailing vehicle flow rates.

To capture the dynamic nature of driver behavior, thru vehicle behavior for the major street is summarized into one- and five-minute groupings. The percentage of stopping vehicles is also summarized for each grouping. Figure 4.1 and Figure 4.2 illustrates this data for a sample location, where the percentage of major street stops is shown for each major street approach along with the corresponding minor street flow rate for each time period grouping. Figures C.1 through C.22 in Appendix C show the one- and five- minute data for the other intersections operating with yellow/red flash.

From minute-to-minute, the percentage of thru vehicles stopping on the major street can range from 0 percent to 100 percent. In a sense this dynamic behavior shows that the intersections are rapidly changing between two-way stop and four-way stop conditions at the intersection. If the intersection were to function as either a two-way stop *OR* a four-way stop, drivers would have a basis for determining the appropriate response for navigating the intersection. However, drivers are unable to develop a reasonable operational expectancy as the intersection does not seem to operate as one form of control or the other, but rather as both forms interchangeably. This contributes to driver confusion.

4.1.3.1 Major Street Stops versus Minor Street Volume

For each intersection the percentage of major street stopping and minor street volume was summarized into five minute time periods. The five-minute period smoothes the drastic fluctuations that occur from minute-to-minute, yet retains the variable characteristic that occurs as a result of changing traffic volumes throughout the hour. Minor street volumes were converted to hourly flow rates and plotted against the percentage of major street stops for each five minute period, as shown in Figure 4.3.

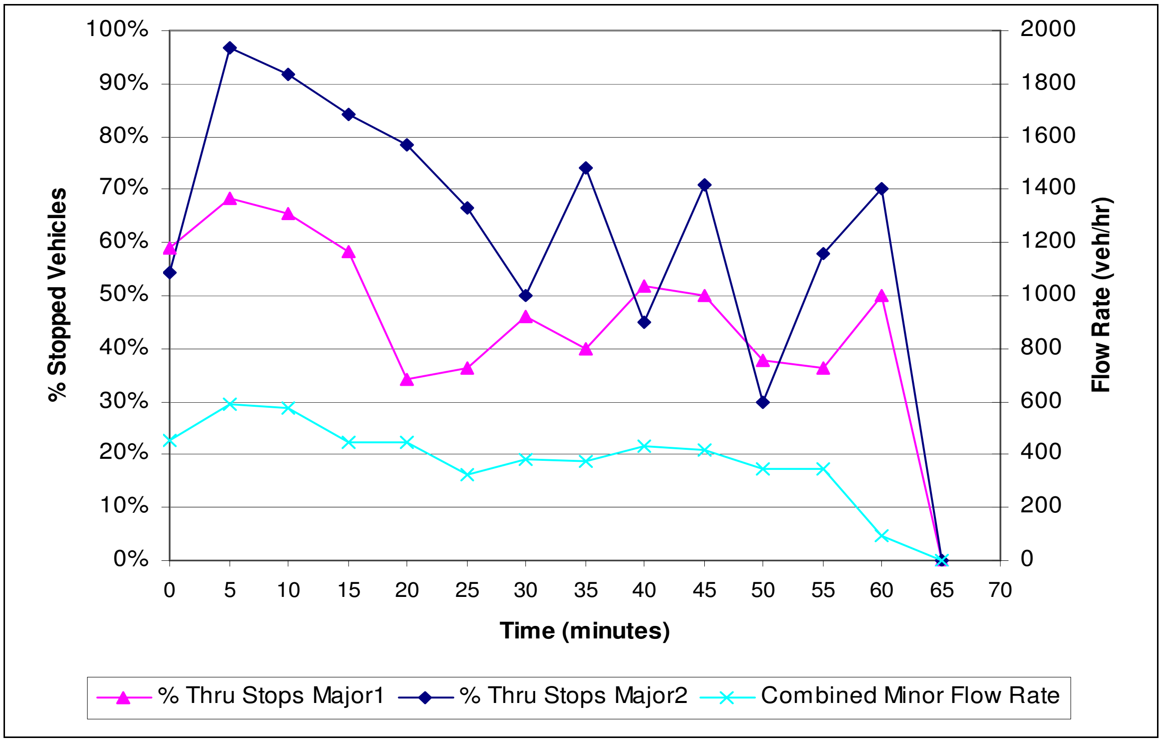


Figure 4.1 Five-Minute Major Street Vehicle Stops and Minor Flow Rate Yellow/Red Flash at Northside Dr./Peachtree Battle Ave. Location

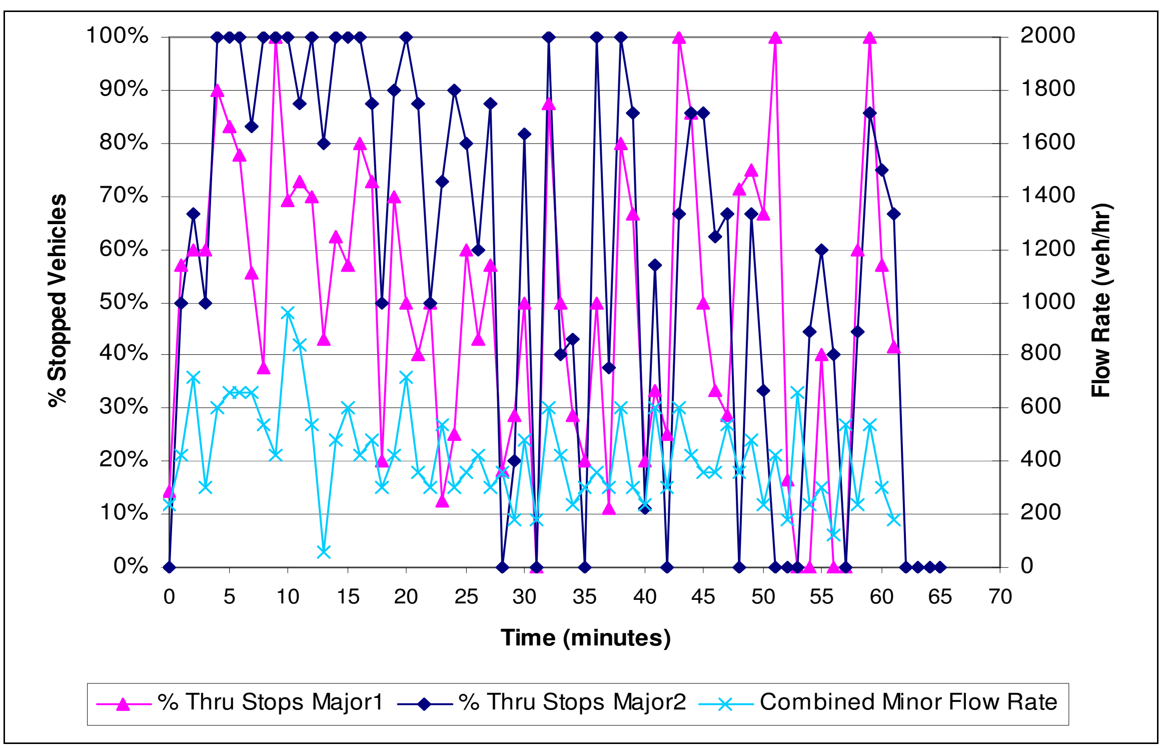


Figure 4.2 One-Minute Major Street Vehicle Stops and Minor Flow Rate Yellow/Red Flash at Northside Dr./Peachtree Battle Ave. Location

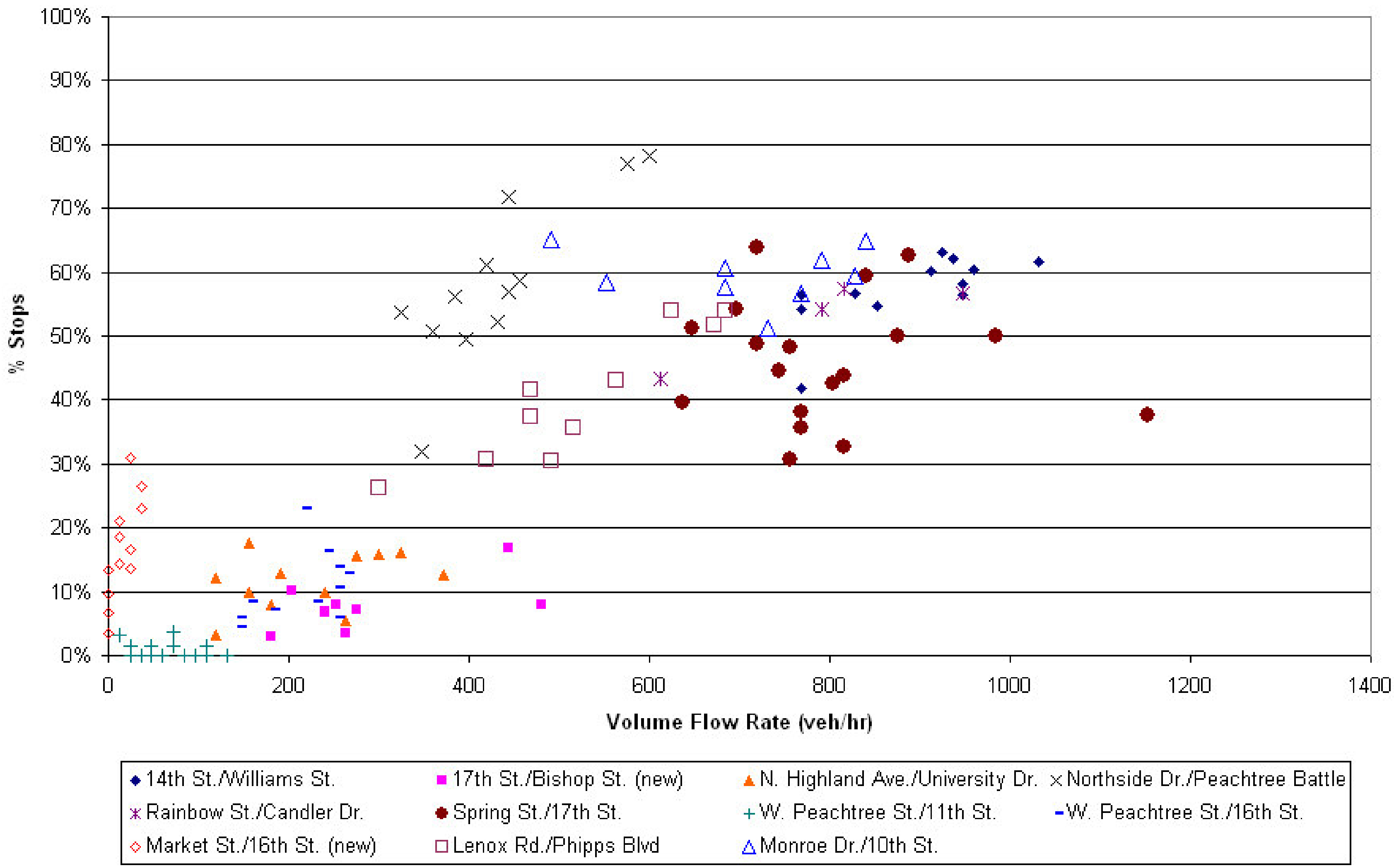


Figure 4.3 Analysis of Major Street Stops (All Vehicles) vs. Minor Street Volume Yellow/Red Flashing

Figure 4.3 shows that as minor street flow rates increase, the percentage of vehicles stopping also increases. It is clear that there is a correlation between the number of vehicles on the minor street and the probability that a major street vehicle will stop on a yellow indication. This is partially explained by the previous observations listed for driver behavior, such as minor street vehicles forcing a gap to make a departure. Thus, the more minor street vehicles present, the greater the chance that a major street vehicle will be forced to stop.

At high minor street flow rates, Figure 4.3 shows that the percentage of major street vehicles stopping is scattered around the range of 40 to 60 percent. At the very lowest flow rates, with fewer than 300 minor street vehicles per hour (vph), fewer than 20 percent of major street vehicles stopped. This low-volume behavior is closer to what would be typically expected for a flashing yellow indication, and is similar to the findings of the FHWA [3] and TTI [4] studies that evaluated flashing signals under low volume conditions. The middle range of data, between 300 and 500 vph show a wide range of values for percentage of vehicles stopping. This is a transitional range, where other factors such as functional classification, number of travel lanes, or distribution of turn movements could have an impact on whether the intersection has a high or low percentage of major street vehicles stopping.

A plot was also created for the stopping behavior of the thru vehicles only and is provided in Figure 4.4. This data shows a little more spread in the range of stopping percentage for the higher minor street flow rates. However, this data follows the same general trends as discussed above.

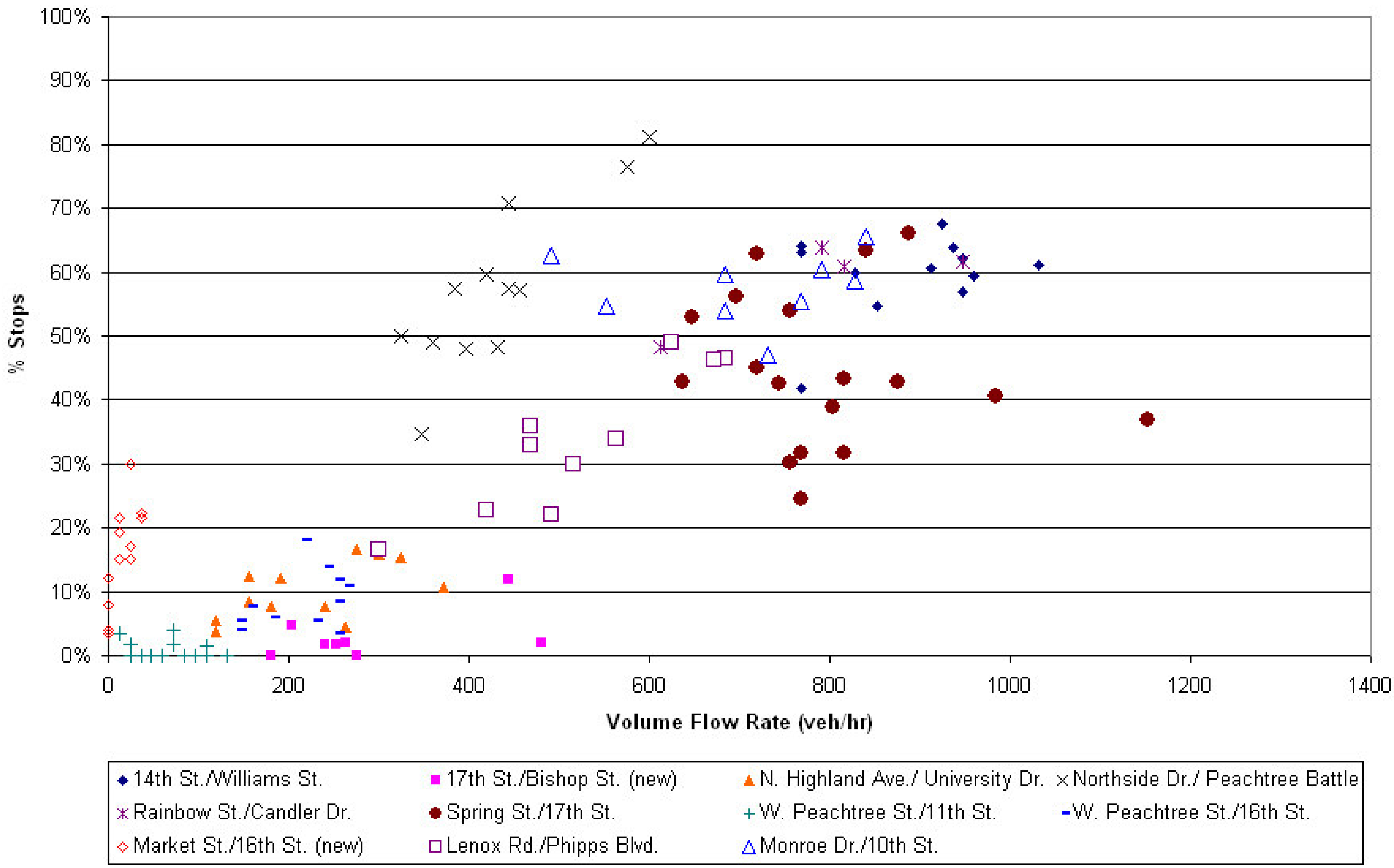


Figure 4.4 Analysis of Major Street Stops (Thru Vehicles) vs. Minor Street Volume Yellow/Red Flashing

The scatterplots of the data shown in Figure 4.3 and Figure 4.4 appear to trend linearly. However, another possibility is that the trendline is “S” shaped instead of linear. This “S” shape would delineate the three distinct regions within the data, with 0 to 200-300 vph showing a relatively flat rate of increase in percent stops. Then in the 300 to 400 vph range, the rate of stopping would increase dramatically, with a near vertical trendline through this region, then flattening out to a relatively low rate of increase again at the higher volume levels. Additional data is required to validate either trend, as drawing conclusions on the specific shape of the trendline may be premature for the quantity of data collected.

4.1.4 Discussion of Findings For Flashing Red/Red Operations

Data was also collected for two signals operating in red/red malfunction flash. Since yellow/red flash is the typical malfunction operation finding signals operating in red/red malfunction flash is a difficult task. Table 4.1 summarizes the stopping behavior observed for the red/red flashing operation. The intersections had average percentages of stopping vehicles of approximately 84.7 percent and 83.5 percent, respectively. These values represent the percentage stopping for all vehicles (not just the thru vehicles) since it is a violation to not stop on a flashing red indication.

Previous studies on operations of flashing signals have assumed that all vehicles at a flashing red/red signal come to a stop. However, the data collected at the two study intersections seems to run contrary to this assumption. While the observed average stopping rate for these two flashing red/red signals seems low, it may actually be somewhat representative of what happens at signals operating normally. A 1989 FWHA study conducted by Pietrucha, et al. [17] evaluated driver compliance with all types of traffic control devices. Field studies found that approximately 90 percent of drivers illegally entered intersections controlled by traffic signals. The study also reported results from a survey of driver attitude toward violations, citing that 3.3 percent of respondents admitted to running a red signal on a daily basis. Thus, a portion of the violation rate may be in line with normal driver behavior, with driver confusion contributing to the higher level of violations than those reported from Pietrucha, et al.

A plot of stopping percentage versus time is provided in Figure 4.5 and Figure 4.6 for one of the study locations. Data is summarized by one- and five-minute periods. While variation from minute-to-minute is still present in the percentage of vehicles stopping for a red indication, the variation is much less severe than at the yellow/red flash intersection. The data for the study location in Figure 4.5 and Figure 4.6 typically varies between 70 and 100 percent stopping, which is much more consistent than the variability noted for yellow/red flashing operation that ranged from 0 to 100 percent stopping. The plots for the second red/red intersection, Roswell Road at W. Wieuca Road, may be found in Appendix D.

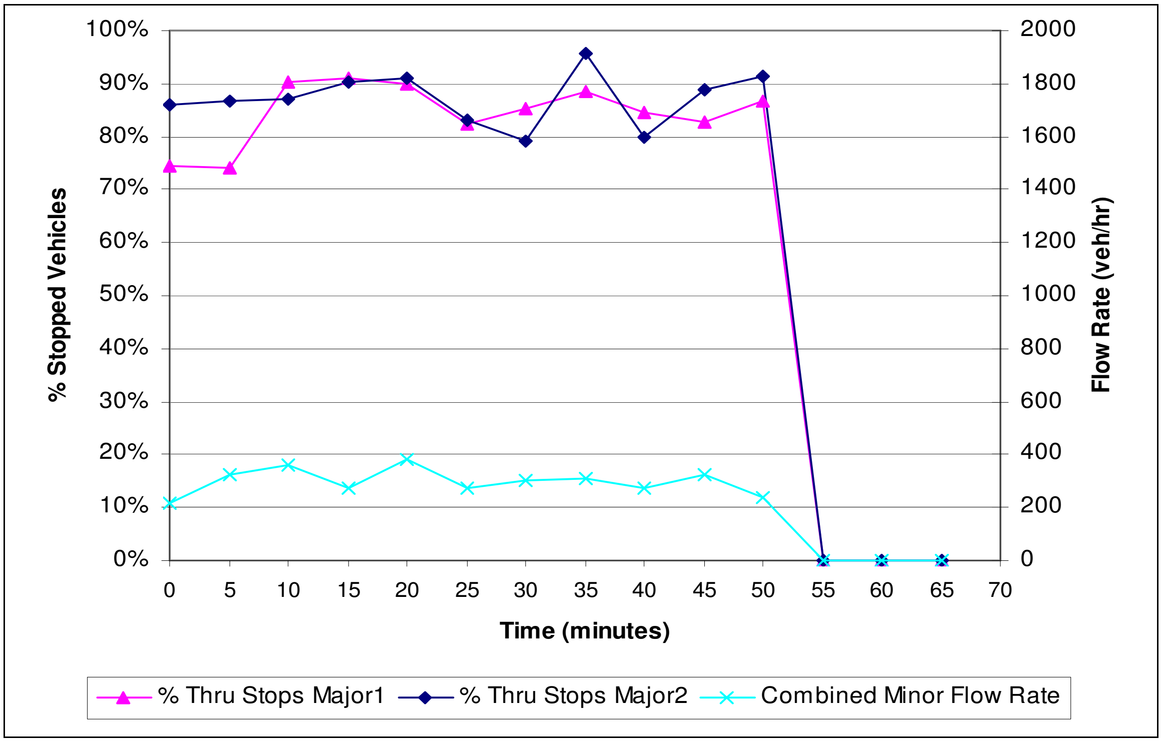


Figure 4.5 Five-Minute Major Street Vehicle Stops and Minor Flow Rate Red/Red Flash at Piedmont Rd./The Prado Location

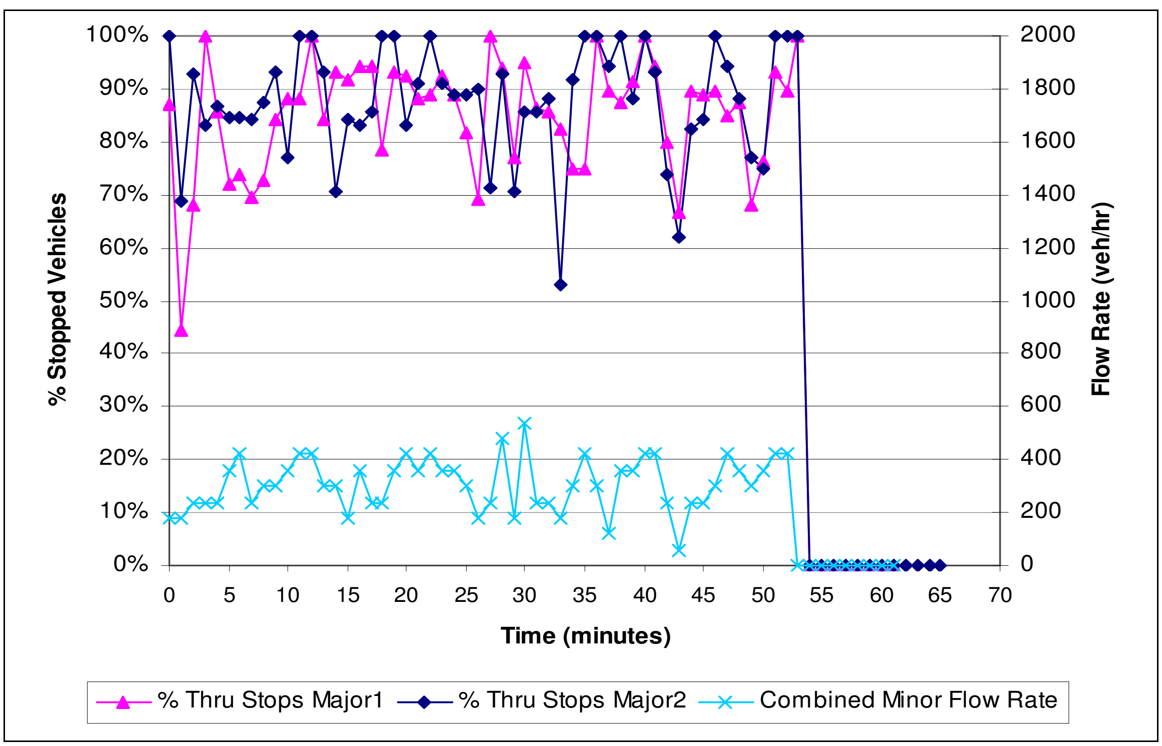


Figure 4.6 One-Minute Major Street Vehicle Stops and Minor Flow Rate Red/Red Flash at Piedmont Rd./The Prado Location

4.1.5 Findings of Stopping Characteristics from Previous Studies

As discussed in Chapter 2 the 1980 FHWA study [3] is the only study to have evaluated flashing signal operations based upon field data. Within this study, measured delay from the field was used to validate a theoretical delay model that could then be used to extrapolate delay estimates into those areas where there were gaps in the data. The delay model was then used to predict the percentage of intersection vehicles stopping at yellow/red and red/red flashing signals. The percentage of vehicles stopping was graphed against the ratio of major street/minor street traffic volumes and is presented in Figure 4.7.

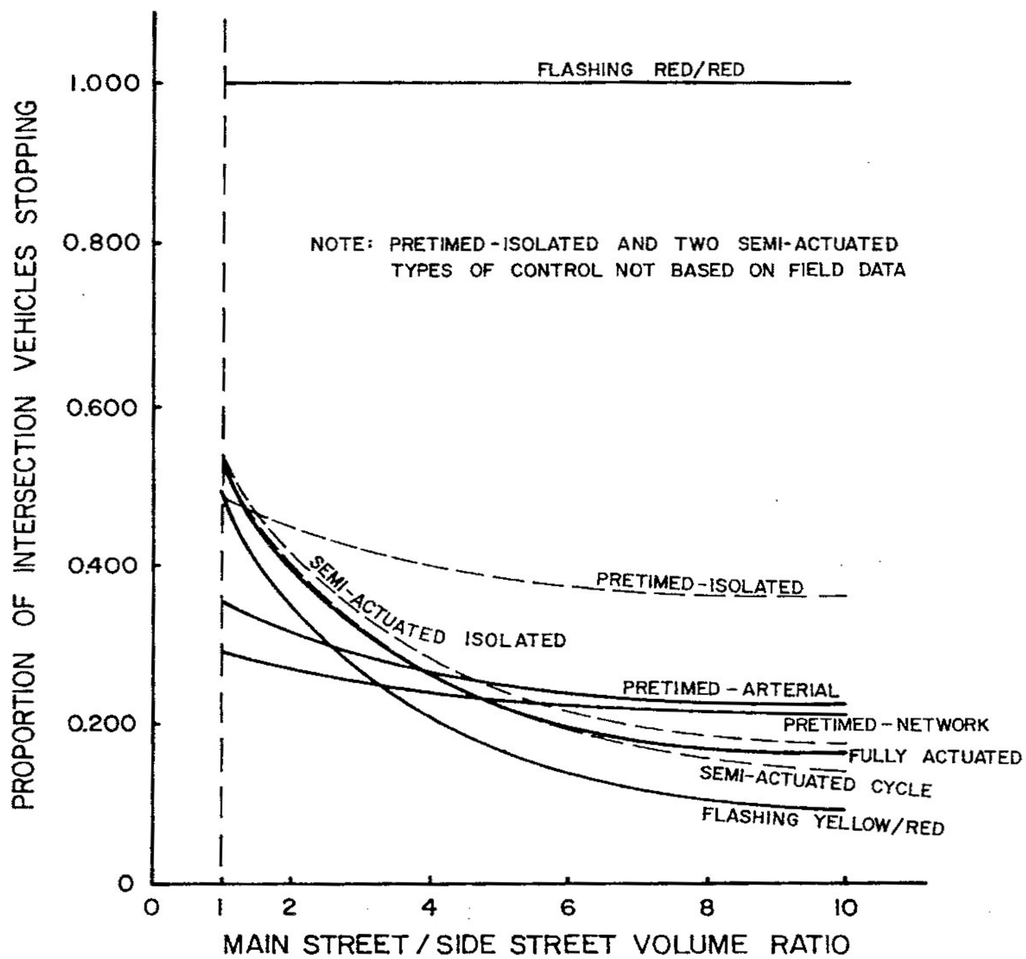


Figure 4.7 Proportion of Intersection Vehicles Stopping [3]

It may be shown that the stop percentages shown on the nomograph in Figure 4.7 simply follow the assumption that all vehicles stop on a red flash and no vehicles stop on a yellow flash. For example, 50 percent of the vehicles are projected to stop at a flashing red signal if the major/minor volume ratio equals 1. This is because half the vehicles are on the red and are expected to stop and the other half are facing a yellow indication and are not expected to stop. Similarly, at a ratio of 4, 20 percent of vehicles are shown to stop, which corresponds to the assumption of 20 percent of the vehicles arriving on the minor approach with the red flash and being required to stop.

Based upon the results presented in Table 4.1, observed driver stopping behavior for yellow and red flashing indications clearly does not match the assumptions made in prior studies. Therefore caution should be exercised when making comparisons of flashing signal operations to other signal modes of operation (such as pre-timed, semi-actuated, or actuated) using the data presented in Figure 4.7.

Much of the previous literature on flashing signals utilizes the ratio of major street/minor street traffic volumes. As discussed in the literature review in Chapter 2, this measure has been used extensively for safety analysis, often with conflicting results. However, to provide some level of continuity with prior studies, the results of the current analysis were plotted to identify the percentage of major street stops versus the ratio of major/minor traffic volumes and is presented in Figure 4.8.

At first glance, the data in Figure 4.8 seems to follow a similar trend to the data presented in the FHWA nomograph shown in Figure 4.7, with the primary exception of higher stop rates at the lower (1 to approximately 3) ratios. However, the piece of the story that is difficult to discern from the graph is that when evaluating the flashing signals

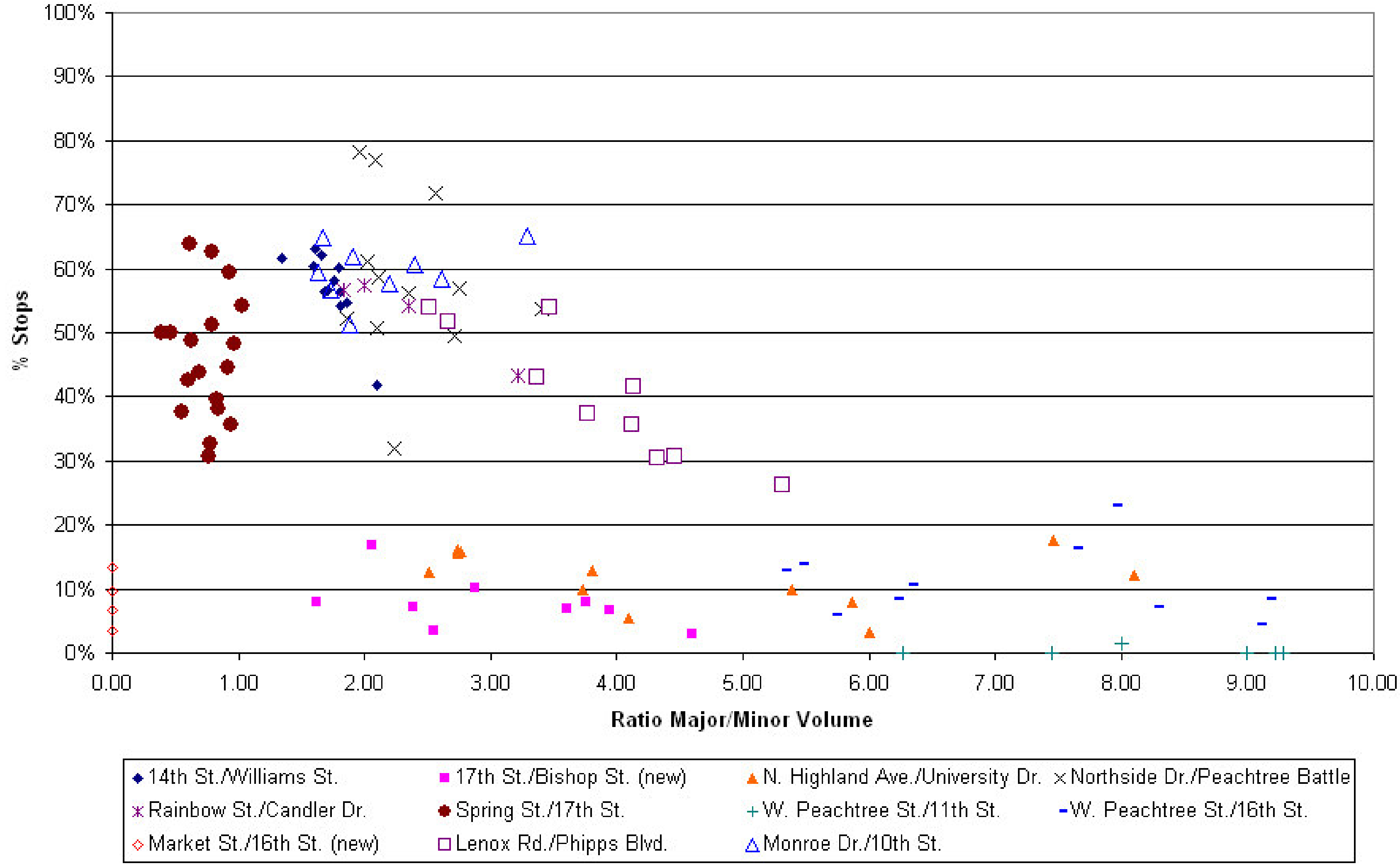


Figure 4.8 Major Street Stops (Thru Vehicles) vs. Major/Minor Volume Ratio Yellow/Red Flashing

from an operational standpoint, rather than a safety one, there is a point at which the measured intersection traffic is controlled by the driver behavior and physical capacity of the intersection rather than by traffic demand. As already seen at higher volume levels an intersection in flashing yellow/red mode will begin operating similar to a four-way stop controlled intersection. At this point, the number of lanes along the major and minor roads essentially meters the vehicle flow rate and the resulting ratio of major/minor volume. For example, an intersection with two lanes on the major street and one lane on the minor will have a traffic count ratio under flashing conditions of 2 to 1 (major to minor) once the intersection reaches capacity. This will be true even if the actual demand at the intersection has a much higher ratio (for example 6 to 1).

Within Figure 4.8, the intersections that are identified with a major/minor volume ratio of approximately 1 each have a similar number of lanes on both the major and minor roadways. Thus, at high volumes, these roadways have a high percentage of major street stopping due to the intersection intermittently operating as a four-way signal, resulting in a value of 1 for the ratio of major/minor volumes due to capacity constraints.

At low flow rates, there is not the same issue with capacity as the level of minor street volume never forces the intersection operations to break down to a four-way stop condition. Locations with low stops and a high ratio in Figure 4.8 are only those intersections with minor street volumes sufficiently low such that the intersection continues to operate as a two-way stop controlled condition. However, as capacity is a constraining issue to the volume ratio at higher demands, the data presented within this analysis references only the minor street volume or flow rate rather than the ratio of flow rate in order to avoid a bias from intersection geometry.

4.2 Analysis of Platoon Stops

Often vehicles were observed to enter the intersection as a platoon of two or more vehicles, where vehicles would "piggyback" the vehicle at the head of the platoon and utilize the same gap without stopping. An example scenario would be a vehicle stopping on a flashing yellow indication with additional cars queuing up behind the stopped vehicle. As the head vehicle departs, one or two of the queued vehicles follow the lead vehicle through the intersection without stopping. While vehicles facing a flashing yellow indication are not required to stop, observations showed that for intersections with moderate to high minor street volumes, the major street would often operate as described above with vehicles moving through the intersection in groups of two or three. This activity was typical of both yellow and red flashing indications.

Analysis was conducted to evaluate the stopping characteristics of the platoons as a group (rather than individual vehicles), by counting the characteristics of only the vehicle at the head of the platoon. For the purposes of this analysis, the vehicle at the head of the platoon is referred to in this analysis as the lead vehicle. Subsequent vehicles, behind the lead vehicle, were considered part of the platoon if the follow up time was less than or equal to three seconds. This follow up time was calibrated based upon random samplings of the videos to identify maximum time gaps between successive vehicles where the vehicles would still be considered to be a platoon.

If a vehicle had a follow-up time greater than three seconds, it was considered the lead vehicle for a new platoon, as were vehicles coming to a complete stop. Any vehicle departing through the intersection as a single vehicle was counted as a lead vehicle and thus counted as its own platoon. Platoons were identified by approach, thus vehicles could be departing from either the same lane or in adjacent lanes as the lead vehicle and would be still counted as part of the platoon provided that they had a follow-up time of three seconds or less.

The analyses of the stopping characteristics for platoons was summarized for thru movements only, since it was assumed that vehicles turning left or right would potentially have additional conflicts that would make them more likely to stop. Table 4.2 provides a summary of the analysis results. Appendix E provides the one and five-minute data plots for the intersections operating in yellow/red flash mode. Data for the two intersections with red/red flash operation is provided in Appendix F.

This analysis indicated that the percentage of vehicles stopping on any flashing indication was typically higher when evaluating based upon entire platoons instead of each individual vehicle. The difference in stopping percentage ranges from –0.1 percent to +23.2 percent, with an average increase of about eight percent. This result is reasonable since those vehicles within the queue that did not stop are removed from the analysis. However, the difference between the percentage of platoons stopping and the percentage of individual vehicles stopping was not as great as was initially expected.

At intersections with low minor street volumes, the major street platoon stopping percentage remains relatively low. This likely is a result of the number of conflicts from minor street vehicles being low, which equates to the number of lead vehicles stopping also being low. At intersections with high minor street volumes, the major street platoon stopping percentage is again higher than when counting all vehicles. There is not a proportionate increase in percentage of major street stops between the study locations with high and low minor street volumes.

Table 4.2 Platoon Stopping Characteristics

	Intersection Name	# Major Street Platoons – Thru Vehicles Only *[Total Major Thru Volume]*	% Major Thru Stops *[# Stops}*	% Platoon Stops – Thru Vehicles Only *[#Stops]*	Difference in % Stops
Malfunction Yellow/Red Flash	Northside Dr. at Peachtree Battle Ave.	642 *[842]*	58.6 % *[493]*	69.6% *[447]*	+ 11.0 %
	Monroe Dr. at 10th St.	425 *[838]*	57.8 % *[484]*	69.9 % *[297]*	+ 12.1 %
	Rainbow St. at Candler Dr.	175 *[494]*	57.9 % *[286]*	81.1% *[142]*	+ 23.2 %
	N. Highland Ave. at University Dr.	552 *[839]*	9.8 % *[82]*	14.5% *[80]*	+ 4.7 %
	Lenox Rd. at Phipps Blvd.	520 *[1363]*	32.9 % *[449]*	41.7% *[217]*	+ 8.8 %
	Spring St. at 17th St.	367 *[705]*	45.4 % *[320]*	54.0% *[198]*	+ 8.6 %
	W. Peachtree St. at 11th St.	495 *[1093]*	0.7 % *[8]*	0.6% *[3]*	- 0.1 %
	W. Peachtree St. at 16th St.	265 *[1404]*	8.6 % *[120]*	17.4% *[46]*	+ 8.8 %
	14th St. at Williams St.	565 *[1218]*	59.7 % *[727]*	72.7% *[411]*	+ 13 %
New Signal Yellow/Red Flash	Market St. at 16th St.	380 *[425]*	16.5 % *[70]*	16.6% *[63]*	+ 0.1 %
	17th St. at Bishop St.	310 *[491]*	2.9 % *[14]*	3.6% *[11]*	+ 0.7 %
Malfunction Red/Red Flesh	Piedmont Rd. at The Prado	833 *[1807]*	85.3 % *[1541]*	92.1% *[767]*	+ 6.8 %
	Roswell Rd.at W Wieuca Rd.	741 *[1606]*	83.6 % *[1342]*	90.2% *[668]*	+ 6.6 %

The results indicate that even at intersections with high minor street volumes there is still a portion of vehicles that are not stopping on a yellow flashing indication and are also not within a platoon behind a vehicle that did stop. For example, if 70 percent of the thru platoons were found to stop and 58 percent of thru vehicles stopped, then there would be 30 percent of the vehicles that did not stop and were not within a platoon that stopped. However, in this scenario, the 12 percent difference between lead vehicles and all thru vehicles stop percentage represents those vehicles that were initially captured as not stopping but were actually either stopped behind the lead vehicle or were otherwise influenced by the lead vehicle as part of a platoon.

The study intersections with red/red operation provide the most compelling results. Stop percentages increase under the platoon analysis although they are still substantially lower than the expected 100 percent stopping rate for a flashing red indication. The two study intersections show platoon stopping percentages of 92.1 percent and 90.2 percent. This indicates that even after accounting for vehicles that don't stop as they piggyback onto the lead vehicle that there is still another eight to ten percent of vehicles that are not stopping on a flashing red indication, which matches very well with the violation rates observed in Section 4.4.

4.3 Impact of Minor Street Vehicle Presence on Flashing Operations

Previous literature focused the operational analysis of flashing signals relative to the ratio of major street volumes to minor street volumes. This relationship, originally used to define breakpoints in data for crash experience at low volume intersections operating in program flash, has been subsequently carried on and used for describing delay and stopping characteristics at flashing signals [3] [4]. However, there may be another trend that underlies the pure volume ratio relationship. Observation of the videos suggests that the mere presence of vehicles on the minor street has an impact on major street traffic.

During periods where minor street vehicles were absent, major street traffic facing a yellow flashing indication would generally operate as expected, that is continuous flow through the intersection without stopping. However, upon appearance of a minor street vehicle, the percentage of vehicles stopping on the major street would appear to increase. Additional evidence of the impact of minor street vehicle presence was provided by the one-minute analysis of major street vehicle stopping. At the one-minute level, periods with none or very few vehicles seemed to have lower major street vehicle stop percentages.

4.3.1 Analysis Assumptions

To evaluate the impact of the presence of minor street vehicles on major street traffic, mining of the reduced video data was required to identify the major street vehicles arriving when a minor street vehicle was present and those arriving in the absence of minor street vehicles. Visual Basic scripts were created to enable the analysis. These scripts identified the starting time and ending time that each minor street vehicle was considered “present” at the intersection.

The presence start time for each minor street vehicle was the time that the vehicle came to a stop at the stop line. The presence end time was calculated as the time of departure plus three additional seconds to account for the vehicle navigating through the intersection. For example, if a minor street vehicle came to a stop at time 32:00 minutes and departed six seconds later at time 32:06, the presence start time for that vehicle would be from 32:00 to 32:09 or a total of nine seconds. Each minor street vehicle is assigned their own presence start and end time and then those times are aggregated to provide a running presence time. For instance, if a second vehicle stopped at the intersection at 32:08 and departed at 32:12, then that vehicle would be considered present from 32:08 to 32:15. The running total for the two vehicles would then be from 32:00 to 32:15, indicating a constant minor street presence over that time period.

Major street vehicles were classified by whether they arrive during a period of minor vehicle presence or absence. Due to the format of the reduced data, a major street vehicle arrival was classified by the time the vehicle was identified as stopped or, if the vehicle did not stop, the time that the vehicle crossed the stop bar to departure the intersection. If a minor street vehicle arrived while a major street vehicle was already stopped, the major street vehicle was assumed to be NOT influenced by the minor street vehicle (provided no other minor street vehicle was present at the time the major street vehicle came to a stop). The minor street vehicle is considered present if the major and minor street vehicles arrive at the same time.

4.3.2 Results of Minor Street Vehicle Presence Analysis

Each major street vehicle was identified by whether or not a minor street vehicle was present at the time of the major street vehicle arrival. Each major street vehicle was then further summarized utilizing Excel functions created for mining the reduced video data. Major Street vehicles were segmented into two cases by vehicle presence and then summarized over one and five minute time periods. The cases are as follows:

1. **Case 1 – Minor Street Vehicle Present.** Case 1 data is a subset of the major street thru vehicle data that satisfy the condition for vehicle arrival with a minor street vehicle present.
2. **Case 2 – Minor Street Vehicle Absent.** Case 2 data represents the remaining subset of the major street thru vehicle data that satisfy the condition for vehicle arrival in the absence of minor street vehicles.

For each case, vehicle data was summarized to identify the number of major street vehicles stopping for each case and the corresponding stop percentage. Table 4.3 provides a summary of the data aggregated over the entire duration of the video. Figure 4.9 shows an example of the data from the intersection of Northside Drive/Peachtree Battle Avenue as a function of time for data grouped into five-minute segments.

Table 4.3 Summary of Influence of Minor Street Presence on Major Street Stops

	Intersection Name	Video Length (Min)	Major Thru Volume *[Flow Rate (veh/hr)]*	Minor Thru Volume *[Flow Rate (veh/hr)]*	Case 1 – Minor Street Vehicle Present: Major Thru Volume [% of Total Thrus]	Case 1 – Minor Street Vehicle Present: % Thru Stops	Case 2 Minor Street Vehicle Absent: Major Thru Volume [% of Total Thrus]	Case 2 Minor Street Vehicle Absent: % Thru Stops
Malfunction Yellow/Red Flash	Northside Dr. at Peachtree Battle Ave.	62	842 *[940]*	436 *[536]*	613 *[72.8%]*	**67.7 %**	229 *[27.2%]*	**34.1 %**
	Monroe Dr. at 10th St.	45	838 *[1044]*	531 *[820]*	755 *[90.1%]*	**59.5 %**	83 *[9.9%]*	**42.2 %**
	Rainbow St. at Candler Dr.	23	494 *[1252]*	295 *[780]*	440 *[89.1%]*	**60.2 %**	54 *[10.9%]*	**38.9 %**
	N. Highland Ave at University Dr.	61	839 *[960]*	227 *[272]*	367 *[43.7%]*	**12.0 %**	472 *[56.3%]*	**8.1 %**
	Lenox Rd at Phipps Blvd	52	1363 *[1560]*	441 *[660]*	1106 *[81.1%]*	**34.8 %**	257 *[18.9%]*	**24.9 %**
	Spring St. at 17th St.	90	705 *[548]*	1199 *[956]*	626 *[88.8%]*	**47.8 %**	79 *[11.2%]*	**26.6 %**
	W. Peachtree St. at 11th St.	85	1093 *[880]*	88 *[52]*	174 *[15.9%]*	**1.2 %**	919 *[84.1%]*	**0.7 %**
	W. Peachtree St. at 16th St.	61	1404 *[1596]*	212 *[212]*	1083 *[77.1%]*	**10.0 %**	321 *[22.9%]*	**3.7 %**
	14th St. at Williams St.	60	1218 *[1292]*	888 *[928]*	1197 *[98.3%]*	**60.2 %**	21 *[1.7 %]*	**28.6 %**
New Signal Yellow/Red Flash	Market St at 16th St.	62	425 *[484]*	14 *[12]*	13 *[3.1%]*	**38.5 %**	412 *[96.9%]*	**15.8 %**
	17th St. at Bishop St.	46	491 *[652]*	214 *[384]*	222 *[45.2%]*	**4.1 %**	269 *[54.8%]*	**1.9 %**
Malfunction Red/Red Flesh	Piedmont Rd. at The Prado	50	1807 *[2124]*	274 *[304]*	1193 *[66.0%]*	**88.7 %**	614 *[34.0%]*	**78.7 %**
	Roswell Rd.at W Wieuca Rd.	63	1606 *[1580]*	740 *[784]*	1437 *[89.5%]*	**85.4 %**	169 *[10.5%]*	**68.1 %**

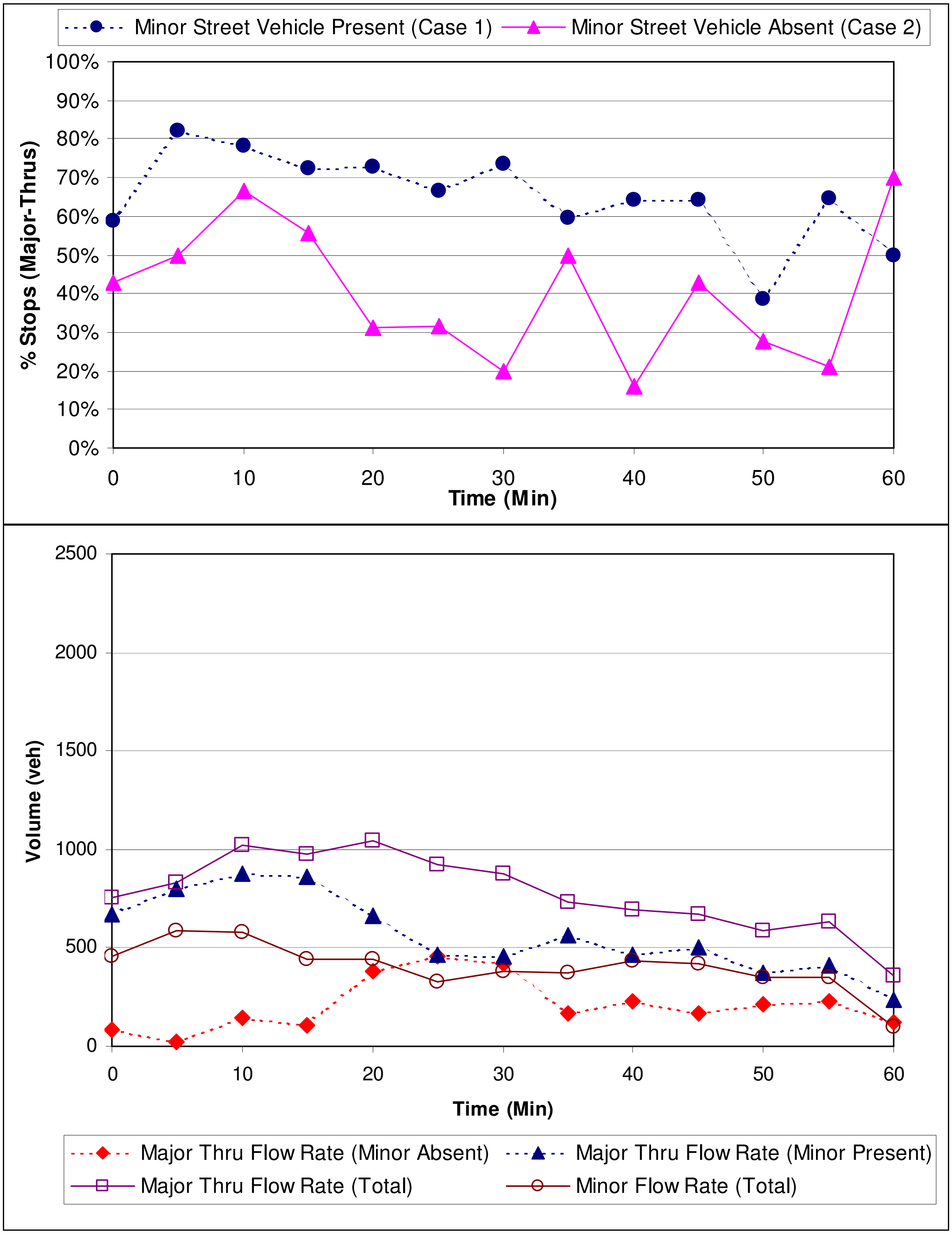


Figure 4.9 Major Street Thru Stops and Volumes in the Presence and Absence of Minor Vehicles at Northside Dr./Peachtree Battle Ave. Location

4.3.3 Summary of Minor Street Presence/Absence Analysis Findings

For each study intersection, major street thru vehicles had a decrease in the percentage of vehicles stopping when a minor street vehicle was absent. Results vary based upon the minor street flow rate; however, a number of general conclusions can be drawn from the findings. The following bullets identify a few results from the analysis:

- The difference in major street thru vehicle stopping between Case 1 and Case 2 conditions ranged from 0.5 percent to 33.6 percent.
- An average difference of 15.5 percent was found in major street thru stopping for all intersections operating in yellow/red flash mode.
- Study intersections operating with red/red flash were found to have a decrease of approximately 13.7 percent in major street thru stops where the minor street was absent of vehicles.
- Even in the absence of minor street vehicles, an average of approximately 20 percent of major street thru vehicles were found to stop when facing a yellow indication. This value range from 0.7 percent to 42.2 percent.

The analysis results show that even in the absence of minor street vehicles, major street thru vehicles are stopping at a rate as high as 40 percent on a flashing yellow indication. This indicates a high level of driver confusion at flashing yellow signals where drivers are stopping even in the absence of minor street conflict. A portion of this stopping percentage could be attributed to the presence of conflicting major street left-turning vehicles or observing other mainline vehicles stopping upon arrival at the intersection. However, the relative percentage of left-turning vehicles is assumed to be constant for both the Case 1 (present) and Case 2 (absent) conditions and therefore should have a minimal affect on the net difference in stopping percentage between the two cases. Although, future analysis will investigate the potential impact of left turning vehicles presence vs. absence on major street vehicles stopping percentages.

For signals flashing yellow/red, the percentage of major street thru vehicles stopping under Case 1 conditions ranges from 1.2 percent to 67.7 percent. This range in percentage of stopping is directly affected by the flow rate of minor street vehicles as previously discussed in this chapter. With such a wide range in the percentage of major street vehicles stopping at a flashing yellow indication, it can be difficult for drivers to develop an expectancy for the actions of other drivers around them. This variation in stopping percentage can lead to potential safety issues, particularly for the interaction of major and minor street vehicles. The greater the percentage of the major street vehicles that are stopping at a given intersection, the greater the chance that minor street drivers will build up false expectations that all vehicles are supposed to stop. This can lead to the minor street driver pulling out in front of a major street vehicle that does not stop, potentially resulting in a dangerous high-speed right angle collision. Plots of the presence and absence data analysis over one and five-minute time periods at intersections with yellow/red flash is provided in Appendix G.

For signals flashing in red/red mode, the percentage of thru stops on the major street were 88.7 percent and 85.4 percent when a minor street vehicle was present, but only 78.7 percent and 68.1 percent of major street thru vehicles stopped when minor street vehicles were absent. This suggests that vehicles are more likely to violate the red signal display under lower volume conditions where the absence of conflicting traffic is more likely. However, even though a large percentage of vehicles are being recorded as not stopping, nearly all vehicles were observed to reduce their speed to a slow rolling condition as they enter the intersection, reducing the potential for severe accidents. Appendix H provides one and five-minute plots of the presence and absence data analysis for each of the intersections with red/red flashing operation.

Additional data is required to validate the results of the analysis and whether the presence or absence of a minor street vehicle is having an affect on the behavior of major street drivers. There are few data points within the set of study intersections where major street traffic flow is moderately balanced between minor street vehicle presence and absence conditions. These are the conditions best suited for testing the impact of presence, since there will be equal opportunities for both presence and absence of minor street vehicles, without reaching a capacity constraint. At the higher volume intersections, capacity constraints limit the number of instances in which a minor street vehicle is absent, thus it is difficult to determine if the percentages of stops for the few sample vehicles arriving in the absence of a minor vehicle is truly representative of the population.

4.4 Violations of Signal Control

In maintaining safe operating conditions, it is important for drivers to adhere to the requirements of the signal indications. Violations of a signal, such as failing to stop on a solid or flashing red indication may increase the crash potential of the intersection. Each of the study intersections was evaluated to identify the number of violations of the signal display. Table 4.4 provides a summary of the number of violations per 100 vehicles entering the intersection for the respective major and minor approaches.

Table 4.4 Violations per 100 Vehicles of Flashing Study Locations

	Intersection Name	Approach	Volume (Vehicles)	# of Violations	# Violators Departing as Platooned Vehicles*	Violations per 100 Vehicles
Malfunction Yellow/Red Flash	Northside Dr. at Peachtree Battle Ave.	Major Minor	1029 436	0 0	0 0	**0** **0**
	Monroe Dr. at 10th St.	Major Minor	1099 531	0 112	0 70	**0** **21.1**
	Rainbow St. at Candler Dr.	Major Minor	711 295	0 131	0 42	**0** **44.4**
	N. Highland Ave. at University Dr.	Major Minor	919 227	0 0	0 0	**0** **0**
	Lenox Rd. at Phipps Blvd.	Major Minor	1631 441	0 91	0 61	**0** **20.6**
	Spring St. at 17th St.	Major Minor	883 1199	0 277	0 175	**0** **23.1**
	W. Peachtree St. at 11th St.	Major Minor	1171 88	0 0	0 0	**0** **0**
	W. Peachtree St. at 16th St.	Major Minor	1495 212	0 15	0 5	**0** **7.1**
	14th St. at Williams St.	Major Minor	1522 888	0 236	0 191	**0** **26.6**
New Signal Yellow/Red Flash	Market St at 16th St.	Major Minor	456 14	0 1	0 0	**0** **0.7**
	17th St. at Bishop St.	Major Minor	608 214	0 94	0 24	**0** **43.9**
Malfunction Yellow/Red Flash	Piedmont Rd. at The Prado	Major Minor	1918 274	293 6	218 2	**15.3** **2.2**
	Roswell Rd.at W Wieuca Rd.	Major Minor	1900 740	314 145	217 45	**16.5** **19.6**

*Represents violating vehicles that depart as a platoon by "piggybacking" the vehicle ahead of it.

For the purposes of this analysis, violations were identified as any vehicle not stopping on a flashing red indication. Violations were not recorded for the major approaches with a flashing yellow indication as a vehicle stopping on a yellow indication was not considered a violation. This definition is consistent with previous studies of violations completed for nighttime program flash operation [3] [4]. The past studies of violations during nighttime conditions summarized in the Chapter 2 literature review indicated a wide range of violation rates, with rates as high as 6.15 violations per hundred vehicles for approaches with a flashing red signal indication.

Table 4.4 provides a summary of the number of violations recorded at each of the study intersections. Generally, the intersections with low minor street volumes had either no or few violations. At several intersections with high traffic volumes a large number of violations were observed. However, high volumes alone did not necessarily equate to violations of a flashing red signal indication. At some intersections, such as Northside Drive at Peachtree Battle, no violations were recorded.

Violation rates indicate that in excess of 40 percent of vehicles at some intersections failed to stop at a flashing red indication. Some of these vehicles departed by piggybacking with the vehicle ahead of it, utilizing the gap accepted (or created) by the lead vehicle to get through the intersection. These vehicles were recorded as violators since they did not stop at the stop line, even though they may have previously been stopped in a queued state.

At signals with red/red flashing operation, violation rates ranged from 15.3 to 16.5 per hundred vehicles for the major streets and from 2.2 to 19.6 violations per hundred vehicles for the minor streets. These violation rates support the stopping percentage analysis, which identified that a large number of major street vehicles are failing to stop on a flashing red indication.

4.5 Safety and Driver Expectancy at Flashing Signals

4.5.1 Observations of Crashes During Field Data Collection

Three crashes were recorded at the study intersections over the 12 hours and 45 minutes of total video data collected. Two of the crashes were recorded at intersections with flashing yellow/red, one crash a rear-end collision and the other a right angle. An additional right angle crash was also recorded at a signal flashing red/red. The angle collision at the intersection with flashing yellow/red operation was the most severe due to the high speed of the vehicle on the minor street, which drove through the red flashing signal without stopping. The rear-end collision at the intersection with flashing yellow/red operation occurred when a vehicle stopped on a flashing yellow indication and was subsequently hit by a following vehicle. The angle collision at the intersection with red/red flash operation could be referred to as a "fender bender" as at the time of impact both vehicles were traveling at a low speed and were able to clear out of the intersection within a matter of seconds. An additional (fourth) collision was also noted at an intersection with yellow/red flashing operation. This collision, a rear-end, occurred just prior to the data collectors arriving at the intersection, where a police officer was already present and therefore video data was not collected at this location.

The three recorded crashes result in a crash rate of 143.5 crashes per million entering vehicles. This is based upon a combined entering volume of 20,900 vehicles at the 13 study intersections. Additional data is required to validate this extremely high crash rate, however the fact that incidents were recorded at nearly one-fourth of the study intersections (during the average of one hour of video data collection per site) is an indicator of a potential safety problem at signals in malfunction flash.

4.5.2 Discussion of Driver Expectancy and Safety Implications

The discussion of the analysis findings reported in Sections 4.1 through 4.4 of this report have identified driver behaviors at flashing signals that indicate driver confusion and uncertainty, particularly with regard to a high degree of vehicle stopping on a yellow indication. This confusion can have an affect on safety, particularly due to problems with driver expectancy. For example, a minor street vehicle joining the back of the queue sees the intersection operating as a four-way stop, with the vehicles at the front of the queue taking turns with the major street traffic in departing through the intersection. As the vehicle moves up the queue to the stop line, the driver develops an expectation that the intersection operates as a four-way stop. Once the driver reaches the stop line they assume that it is their turn to go and enter into the intersection. Should the major street be under yellow flash and the drivers on the major street at that instance believe they have the right-of-way an incident becomes highly likely.

Clearly, driver expectancy at a signal with flashing yellow/red operation can be a serious issue. As discussed in Chapter 2, driver surveys conducted by the FHWA [3] and TTI [10] identified that drivers faced with a flashing red signal had a low understanding of what the cross-street traffic would be doing (i.e. does the cross-street have a flashing yellow or flashing red indication). The FHWA study found that over 60 percent of the survey participants either thought the cross street would stop or they could not tell what the cross street traffic would do. The TTI study found that 41 percent of drivers surveyed thought that the cross street would stop and another 41 percent could not tell what the cross street traffic would do. Only 13.8 percent of the drivers in the TTI study assumed that the vehicles on the cross street would not stop. This is compared with 39.4 percent for the FHWA study. These numbers indicate that there is a high level of confusion for drivers facing a flashing red indication, where many drivers may incorrectly assume that opposing traffic is either also being displayed a flashing red or should stop for a flashing yellow indication, resulting in an accident.

Based upon the high degree of vehicle stopping on a flashing yellow signal, the problem with driver expectancy is compounded since the driver facing a flashing red has no mechanism for determining whether the cross street is facing a flashing yellow or red indication since some drivers are stopping and some are not. Vehicles consistently stopping on a flashing yellow could even lead a driver to the incorrect expectation that vehicles on a flashing yellow should stop. This could result in an incident at the next flashing signal the driver goes through where it is not treated as a four-way stop.

Rear-end accidents are another likely crash type on the approaches with flashing yellow indications. This is due to the high variability in stopping patterns of drivers from minute to minute as documented in this report. This could lead to accidents where a driver may not be expecting the vehicle in front of them to suddenly come to a stop.

4.6 Analysis Summary

The analysis presented in Chapter 4 evaluates driver behavior at signals operating in malfunction flash based upon field data. Driver behavior characteristics that are evaluated include the propensity of vehicles to stop on both a red and yellow indications and the effect of vehicle platooning on the stop rate. The rate of vehicle stopping is further explored for the effect of the presence or absence of a minor street vehicle on whether or not a major street vehicle will stop.

At each of the study intersections violation rates are identified for vehicles failing to stop on a red indication. Both vehicles stopping on a yellow indication and a failure of drivers to stop on a red indication contribute to a reduction in vehicle safety. A summary is provided of the three crashes recorded during video data collection, with further discussion of issues regarding driver expectancy and the safety implications of the unpredictable driver behavior at signals operating in malfunction flash. Key findings from the research analyses presented in Chapter 4 are summarized in Chapter 5.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Traffic signals operating in malfunction flash mode have long been considered random events, where the operational and safety implications are not well understood. Several studies have been completed that document flashing signal performance under low-volume conditions, particularly during late night/early morning hours of the day. However, there is little evidence that the late night/early morning operational and safety experience translates to higher volume daytime conditions, should a signal malfunction and enter flash mode. This research study was conducted to characterize traffic operations at malfunctioning signals, including driver stopping behavior, platooning effects, and effects of minor street vehicles on major street traffic. Some of the key findings of the study are identified below.

5.1 Analysis Findings

The research summarized in this report evaluated field data collected at signals in malfunction flash to identify driver behavior and operational characteristics. This data fills in a gap in the currently available literature to provide practitioners with an improved understanding of the how a flashing signal operates under medium to high traffic volumes and the safety implications that could arise based upon driver behavior at signals. Two-way major street vehicle flow rates at the study intersections ranged from 508 veh/hr to 2280 veh/hr. Previous studies were generally limited to a two way major street flow rate of less than 400 veh/hr.

5.1.1 Analysis of Vehicle Stopping:

The following list of finding were identified based upon the analysis of vehicle stopping behavior from field data collected at the 13 study intersections:

1. The rate of vehicles stopping on a flashing yellow indication ranged from 0.7 percent to 59.7 percent. This rate varied by location based upon the volume demand present at each study intersection.
2. The rate of vehicles stopping on a yellow indication appears to be strongly correlated to the minor street flow rate. However more data is required to validate the observed trends. The data shows three distinct ranges of minor street volumes, each with different characteristics for the percentages of vehicles stopping on a yellow indication:
    a. At low minor street flow rates (less than 200 vph), the percentage of vehicles stopping on a yellow indication is relatively low with fewer than 20 percent of vehicles stopping at malfunctioning signals.
    b. The middle range of flow rates, 300 to 500 vph, is a transitional area where the percentage of vehicles stopping on the yellow varies widely and may be influenced by other factors such as functional classification, number of travel lanes, or distribution of turn movements.
    c. For minor street volumes in excess of 500 vph, the percentage of mainline vehicles stopping on the yellow generally falls within the range of 40 to 60 percent.
3. Vehicle stopping behavior at yellow flashing indications is dynamic and was observed to vary rapidly from minute to minute with stopping percentages

varying from 0 to 100 percent. This dynamic behavior shows that intersection operations are continuously transitioning between two-way and four-way stop conditions.

4. For the two study intersections with Red/Red flashing operation, the percentage of all major street vehicles stopping was 84.7 percent and 83.5 percent. These rates may be somewhat representative of driver behavior at signals under normal operating conditions, where up to 10% of drivers have been observed violating the red indication.
5. Red/Red flashing operation has less variability in vehicle stopping in comparison to intersections under yellow/red flash. The data for the study locations generally varied between approximately 70 and 100 percent stopping.

5.1.2 Vehicle Platooning Characteristics

One of the observed characteristics of driver behavior at flashing signals was the tendency for vehicles to depart in platoons of two or more vehicles, where vehicles would "piggyback" the vehicle at the head of the platoon and utilize the same gap without stopping. An evaluation of this behavior resulted in the following findings:

1. When major street stopping was evaluated based upon entire platoons (instead of individual vehicles), percent stops increased by an average of eight percent for intersection with yellow/red flashing operation. The difference in percent stops range from –0.1 percent to +23.2 percent. The difference in percent stops for platoons versus individual vehicles at each study location was not proportionate to the volumes present.

2. Increase in percent stops for platoons versus individual vehicles, indicates that a portion of the individual vehicles identified as not stopping, were actually either stopped behind the lead vehicle in the platoon or were otherwise influenced by the lead vehicle as part of a platoon.
3. At intersections with red/red flashing operation, the analysis of platoon stopping showed an average increase in stops of 6.8 percent. This increased the percent stops at the two intersections to 92.1 percent and 90.2 percent respectively. This indicates that even after accounting for vehicles that don't stop as they piggyback onto the lead vehicle, that there is still another eight to ten percent of vehicle that are not stopping at a red flashing indication.

5.1.3 Impact of Minor Street Vehicle Presence on Flashing Operations

Previous literature focused operational analyses at flashing signals relative to the ratio of major street to minor street volumes. However, observations of video data suggested that the mere presence of a minor street vehicle has an impact on major street traffic. An evaluation of this behavior resulted in the following findings:

1. The absence of a minor street vehicle generally resulted in a decrease in the percentage of major street vehicles stopping for both red/red and yellow/red flashing modes. The relative difference between major street thru stopping percentages when a minor street vehicle was present versus absent ranged from 0.5 percent to 33.6 percent. On average, the percent of thru vehicles stopping was lower by 15.5 percent for the conditions where a minor street vehicle was absent at signals under yellow/red flashing mode.

2. Intersections with red/red flash were found to have a decrease of approximately 13.7 percent in major street thru stops where no minor street vehicles were present.
3. Even in the absence of a conflicting minor street vehicle, drivers on the major street are stopping at a rate as high as 40 percent on a flashing yellow indication. This does not consider the impact of conflicting left turning vehicles from the opposing major street approach, a topic that will be explored in future analyses. Still, the results indicate a high level of driver confusion at flashing yellow signals where drivers are stopping even in the absence of a minor street vehicle.
4. For the two signals with red/red flashing operation, 88.7 and 85.4 percent of major street thru vehicles stopped when a minor street vehicle was present. However when a minor street vehicle was absent, the percent stopping dropped to 78.7 and 68.1 percent at each respective intersection. Therefore vehicles are more likely to violate a flashing red signal display indication during periods where there is no conflicting minor street traffic.
5. Even though a high percentage of vehicles are identified as violating a flashing red signal indication, nearly all vehicles were observed to reduce their speed to a slow rolling condition, thus reducing the potential for a severe crash.

5.1.4 Violations of Signal Control

Violations of a flashing red signal display were identified for each study intersection. The analysis identified a wide range of rates of violations from zero to in excess of 40 violations per hundred vehicles at intersections with yellow/red flashing operation. In comparison, this value greatly exceeds the previous findings reported in the literature that identified rates as high as 6.15 per hundred vehicles during low volume nighttime conditions. No clear pattern is evident based upon the data available. Sight distance, area type, number of travel lanes, and other operational characteristics may be contributing to the observed violations.

At signals with red/red flashing operation, the violation rates supported the data from the stopping analysis, with 15.3 and 16.5 violations per hundred vehicles on the major approaches at the two study intersections. The minor streets for the same intersections had violation rates of 2.2 and 19.6 per hundred vehicles, respectively.

5.1.5 Safety and Driver Expectancy

Three crashes were recorded at the study intersections over the 12.75 hours of video data collected at 13 intersections. Two crashes were recorded at intersections with yellow/red flash with the third crash at a signal with red/red flash. The three recorded crashes result in a crash rate of 143.5 crashes per million entering vehicles, which identifies that a flashing signal may be a potentially hazardous condition for drivers.

5.2 Conclusions

Based upon the analysis findings summarized in Section 5.1, it is clear that confusion exists among drivers approaching a signal in flash mode. The following list identifies conclusions drawn from the analysis findings:

1. A high average rate of vehicles stopping on a yellow indication coupled with the variability in stopping from minute-to-minute creates a potential for crashes and further compounds the problem of driver expectancy by creating a constantly changing environment between a two-way stop condition and four-way stop

condition. The stopping also introduces additional delay, which reduces the operational benefit of utilizing the yellow/red flash mode.

a. Under conditions with low minor street volumes (less than 300 vph), a signal in yellow/red malfunction flash mode operates in a manner similar to the findings of previous literature on low-volume nighttime conditions.

b. Under moderate to high minor street volumes (and major street volumes) a signal in yellow/red flash will likely operate with a high degree of stopping on the major street approaches.

2. Providing one consistent mode of flashing operation may be a reasonable solution to improving driver expectancy and safety. Red/red flashing operation is the preferred mode as it provides a reduction in vehicle speeds for all vehicles while also reducing the variability in the number of vehicles stopping. Although it is recognized that a high level of violations were observed at the two study locations with red/red flash, the number of violations are fewer than were found at many of the signals with yellow/red flash. Additionally, the issue of driver expectancy at signals with yellow/red flash would be removed allowing for a more consistent message to the public that all flashing signals should be treated as a four-way stop.

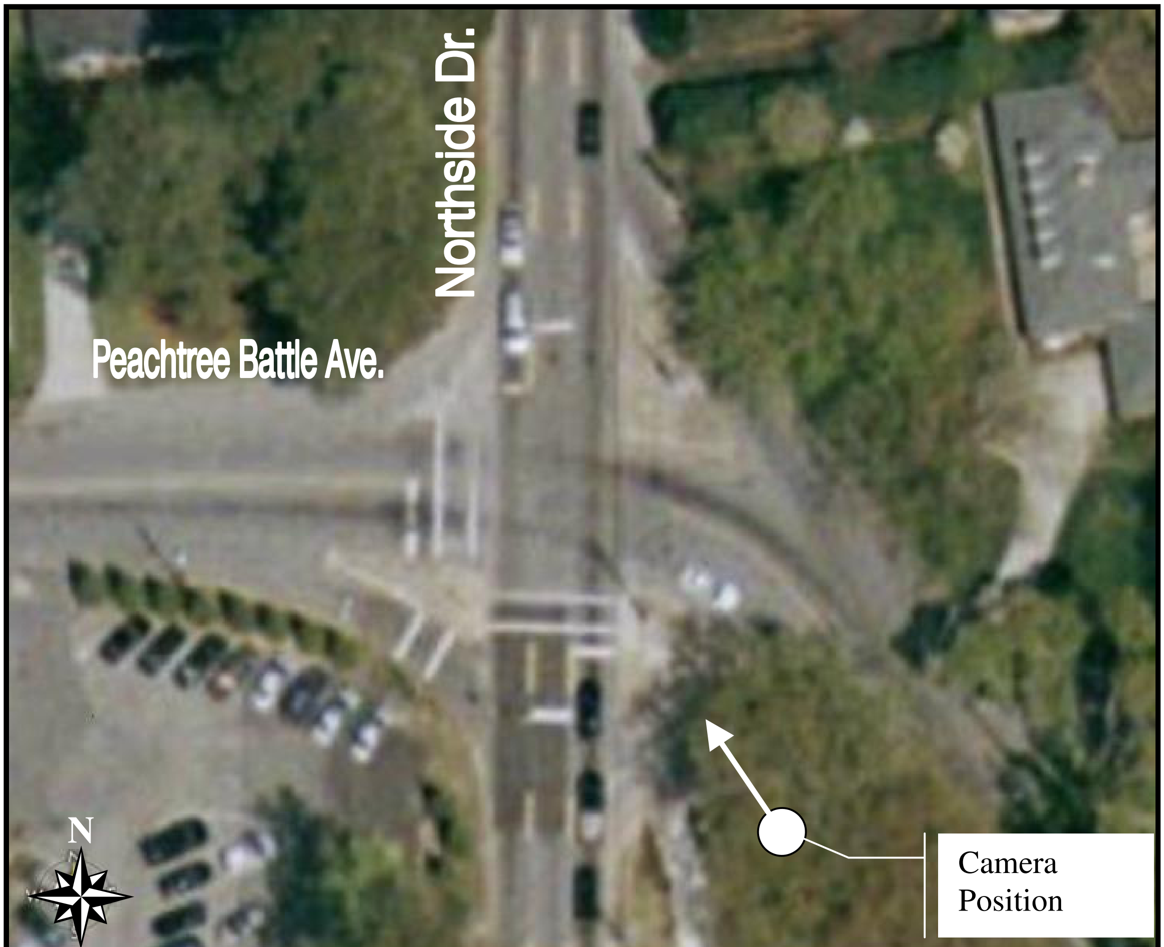
5.3 Recommendations for Future Evaluation

The findings of this research study indicate a need for further evaluation of malfunction signal safety and operations in future research efforts to validate the findings of the research reported in this document and provide additional evaluation for the following topics:

- Evaluate the impact of geometric configuration on flashing operation.
- Evaluate the impact of roadway functional class on flashing signal operations.
- Further evaluate the characteristics of vehicle platoons at flashing signals, such as the relationship between platoon size and approach volume.
- Provide further evaluation of red/red signal performance.
- Evaluate the safety performance of signals operating in flash mode based upon historical crash data.
- Evaluate the effect of conflicting mainline left-turning vehicles.
- Evaluate the difference in control delay between yellow/red and red/red flash modes for moderate to high volume conditions.

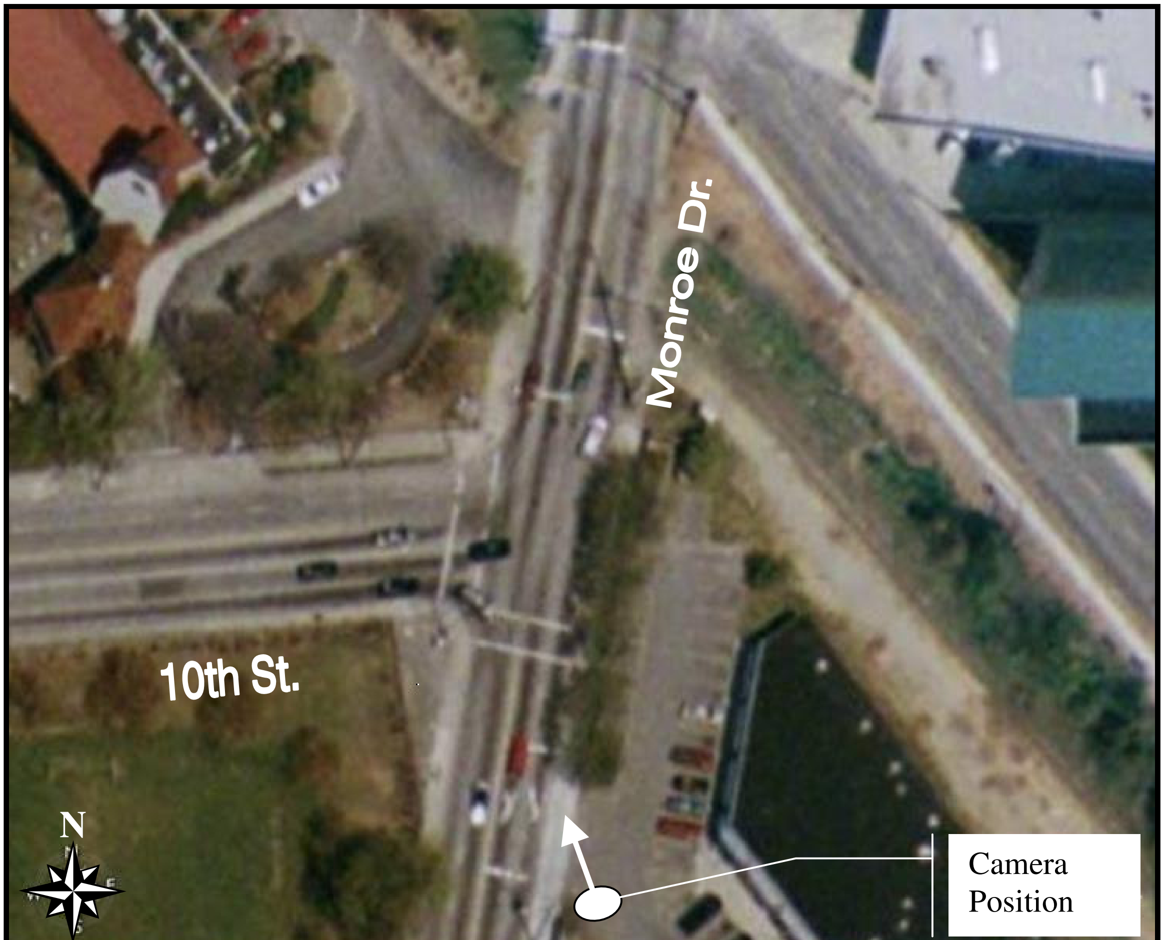
APPENDIX A

AERIAL PHOTOGRAPHS OF STUDY LOCATIONS



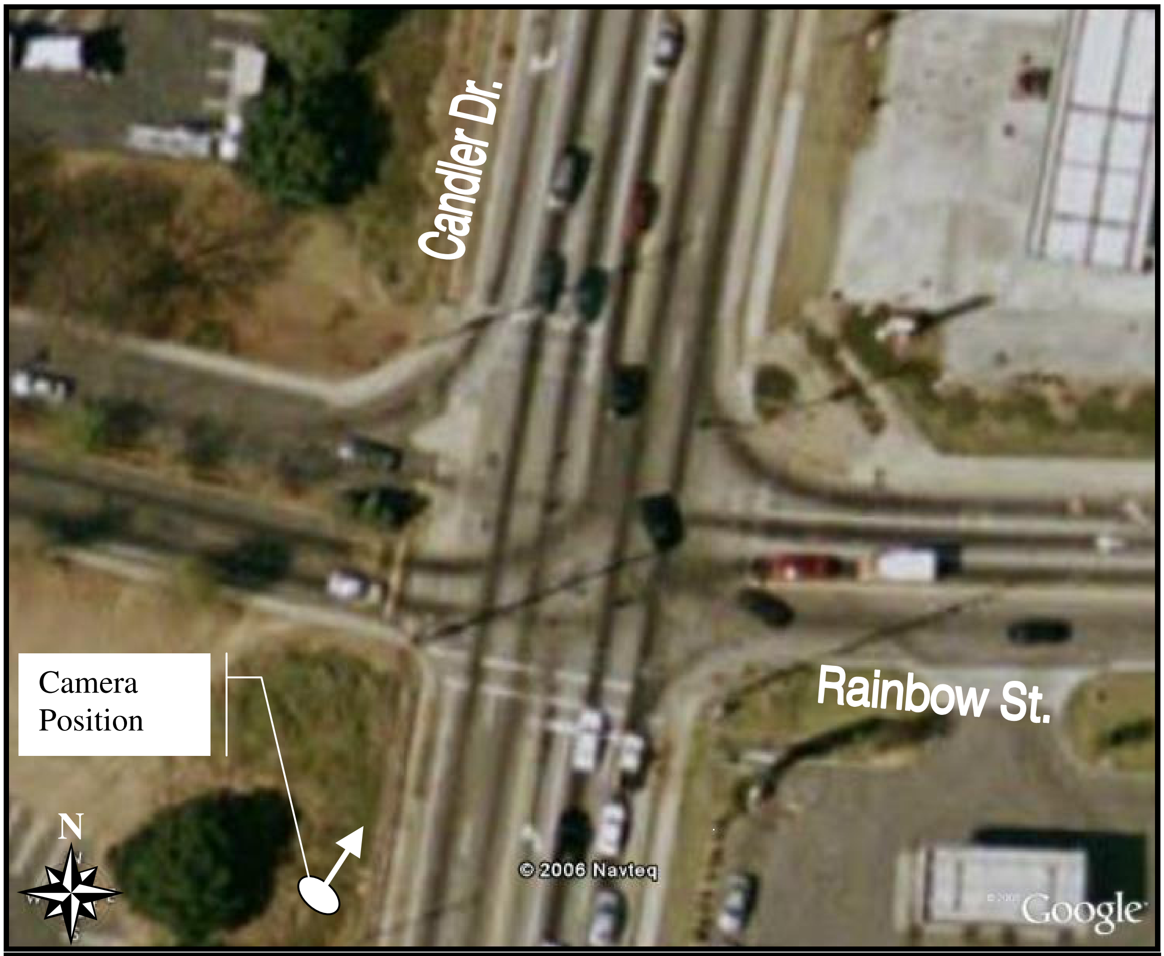
Northside Drive at Peachtree Battle
Atlanta (Fulton County), Georgia

Figure A.1 Aerial Photograph Northside Dr./Peachtree Battle Ave. Intersection



10th Street at Monroe Drive
Atlanta (Fulton County), Georgia

Figure A.2 Aerial Photograph 10th St./Monroe Dr. Intersection



Candler Drive at Rainbow Street
DeKalb County, Georgia

Figure A.3 Aerial Photograph Candler Dr./Rainbow St. Intersection

N. Highland Avenue at University Drive
Atlanta (Fulton County), Georgia

Figure A.4 Aerial Photograph N. Highland Ave./University Dr. Intersection

Lenox Road at Phipps Boulevard
Atlanta (Fulton County), Georgia

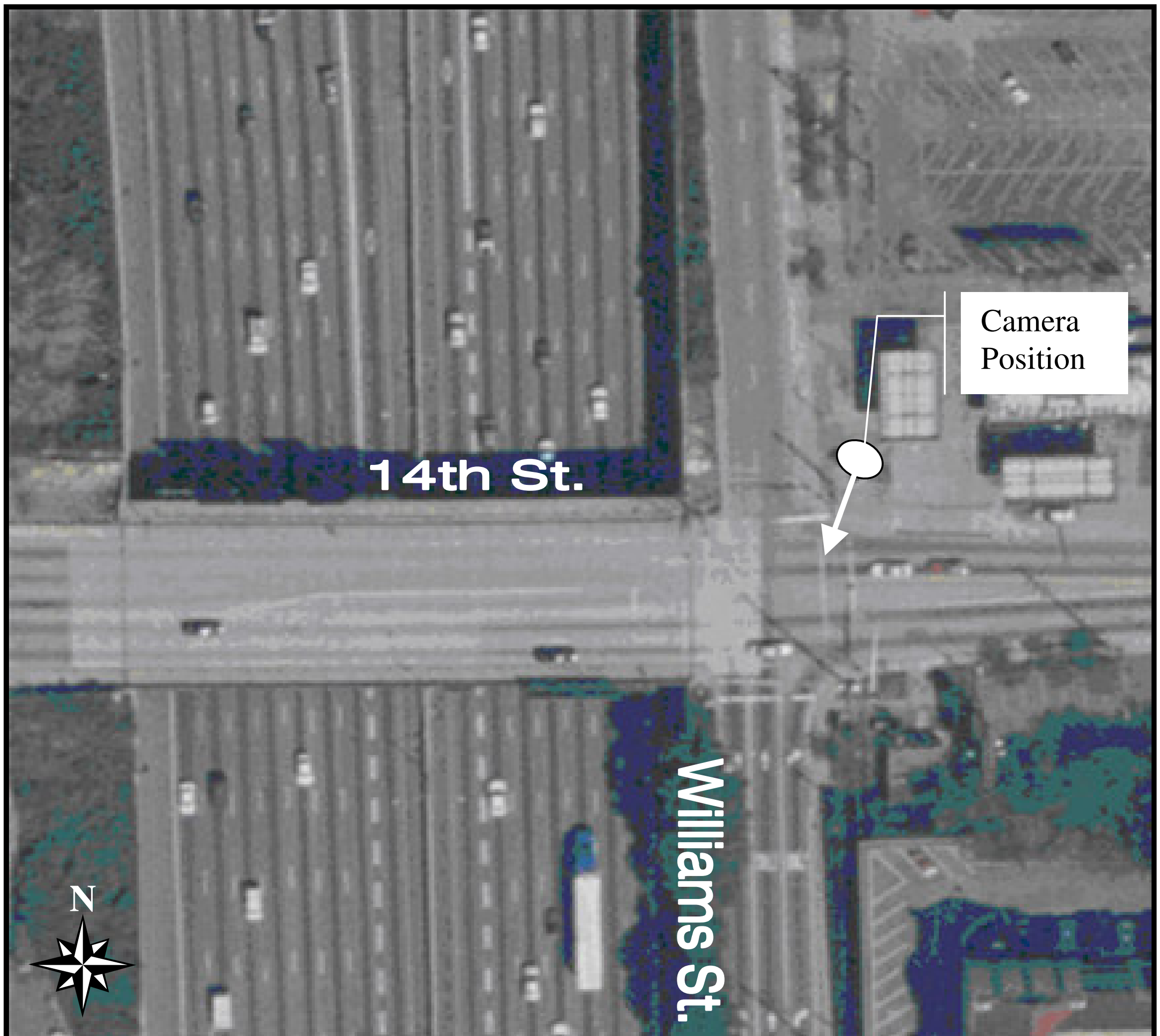
Figure A.5 Aerial Photograph Phipps Blvd./Lenox Rd. Intersection

W. Peachtree Street at 11th Street
Atlanta (Fulton County), Georgia

Figure A.6 Aerial Photograph W. Peachtree St./11th St. Intersection

W. Peachtree Street at 16th Street
Atlanta (Fulton County), Georgia

Figure A.7 Aerial Photograph W. Peachtree St./16th St. Intersection



14th Street at Williams Street
Atlanta (Fulton County), Georgia

Figure A.8 Aerial Photograph 14th St./Williams St. Intersection

17th Street at Bishop St.
Atlanta (Fulton County), Georgia

Figure A.9 Aerial Photograph 17th St./Bishop St. Intersection

Piedmont Road at The Prado / Atlanta Botanical Gardens
Atlanta (Fulton County), Georgia

Figure A.10 Aerial Photograph Piedmont Road/The Prado Intersection

Roswell Rd./W. Wieuca Rd. Intersection
Atlanta (Fulton County), Georgia

Figure A.11 Aerial Photograph Roswell Rd./W. Wieuca Rd. Intersection

The following intersections were recently constructed, within the last three years, and as such aerial photography was not available:

- Spring Street at 17th Street
- Market Street at 16th Street

APPENDIX B

TRAFFIC VOLUME DATA

Table B.1 Traffic Volume Data at Northside Dr./Peachtree Battle Ave.

Car Count		SB			NB			WB			EB			TEV		
Start	End	LT	TH	RT	LT	TH	RT	LT	TH	RT	LT	TH	RT	Interval	Hour	Peak
9:00	9:05	12	39	5	0	24	0	1	8	7	3	18	1	118	1417	#
9:05	9:10	22	38	1	0	31	4	0	7	7	2	29	4	145	1347	
9:10	9:15	9	49	2	2	36	2	3	7	8	5	23	2	148	1202	
9:15	9:20	8	43	3	1	38	2	0	6	7	3	17	4	132	1054	
9:20	9:25	12	41	1	0	46	2	0	2	8	5	21	1	139	922	
9:25	9:30	12	44	1	1	33	1	0	7	3	4	10	3	119	783	
9:30	9:35	8	39	3	0	34	3	2	6	6	3	13	2	119	664	
9:35	9:40	7	30	3	0	31	2	0	8	4	2	14	3	104	545	
9:40	9:45	7	29	1	0	29	1	3	2	7	2	19	3	103	441	
9:45	9:50	11	32	1	2	24	1	1	13	6	3	12	0	106	338	
9:50	9:55	11	29	2	2	20	1	0	6	11	0	10	2	94	232	
9:55	10:00	5	22	2	0	31	1	3	7	4	2	12	1	90	138	
10:00	10:05	6	20	2	0	10	2	1	4	1	0	2	0	48	48	
Total		130	455	27	8	387	22	14	83	79	34	200	26	1465		
Total # of Stops		97	226	8	7	267	9	14	83	79	34	200	26	152	776	122
Average Stop Time (sec)		06.9	05.2	05.9	04.4	05.3	04.2	07.7	06.8	03.0	05.6	06.9	03.7	06.2	06.1	04.2
Average Stop Time (sec)		06.0			04.7			05.8			05.4			05.5		
Max Stop Time (sec)		28.0	23.0	12.0	10.0	18.0	13.0	25.0	22.0	12.0	13.0	43.0	15.0	28.0	43.0	15.0

Table B.2 Traffic Volume Data at Monroe Dr./10th St.

Car Count		SB			NB			EB			WB			TEV		
Start	End	LT	TH	RT	LT	TH	RT	LT	TH	RT	LT	TH	RT	Interval	Hour	Peak
4:50	4:55	0	56	7	18	39	0	21	0	25	0	0	0	166	1630	#
4:55	5:00	0	55	16	21	45	0	19	0	38	0	0	0	194		
5:00	5:05	0	64	11	10	40	0	25	0	32	0	0	0	182		
5:05	5:10	0	67	9	19	40	0	20	0	21	0	0	0	176		
5:10	5:15	0	44	16	18	37	0	28	0	33	0	0	0	176		
5:15	5:20	0	46	12	15	44	0	32	0	38	0	0	0	187		
5:20	5:25	0	47	16	17	33	0	32	0	37	0	0	0	182		
5:25	5:30	0	49	17	18	42	0	27	0	39	0	0	0	192		
5:30	5:35	0	44	13	8	46	0	29	0	35	0	0	0	175		
TOTAL		0	472	117	144	366	0	233	0	298	0	0	0	1630		
Total # of Stops		0	320	40	132	164	0	198	0	221	0	0	0	330	484	261
Average Stop Time (sec)		00.0	07.3	04.9	08.7	04.9	00.0	09.0	00.0	05.5	00.0	00.0	00.0	04.4	03.1	02.6
Average Stop Time (sec)		04.0			04.6			04.8			00.0			03.4		
Max Stop Time (sec)		00.0	32.0	18.0	25.0	15.0	00.0	30.0	00.0	22.0	00.0	00.0	00.0	30.0	32.0	22.0

Table B.3 Traffic Volume Data at Rainbow St./Candler Dr.

Car Count		SB			NB			WB			EB			TEV		
Start	End	LT	TH	RT	LT	TH	RT	LT	TH	RT	LT	TH	RT	Interval	Hour	Peak
3:05	3:10	10	62	17	4	43	0	4	10	11	17	19	7	204	1006	#
3:10	3:15	13	63	38	7	34	0	11	11	8	16	13	7	221		
3:15	3:20	13	87	32	7	25	0	7	7	7	9	17	4	215		
3:20	3:25	14	69	18	7	35	0	8	15	13	16	19	7	221		
3:25	3:30	11	43	22	4	33	0	6	4	6	9	6	1	145		
TOTAL		61	324	127	29	170	0	36	47	45	67	74	26	1006		
Total # of Stops		44	172	14	24	114	0	0	0	0	66	72	26	134	358	40
Average Stop Time (sec)		17.7	10.9	05.2	17.3	19.2	00.0	00.0	00.0	00.0	09.1	09.1	08.8	11.0	09.8	03.5
Average Stop Time (sec)		11.3			12.2			00.0			09.0			08.1		
Max Stop Time (sec)		10.0	36.0	15.0	56.0	43.0	00.0	00.0	00.0	00.0	35.0	40.0	50.0	10.0	43.0	50.0

Table B.4 Traffic Volume Data at N. Highland Ave./University Dr.

Car Count		SB			NB			WB			EB			TEV		
Start	End	LT	TH	RT	LT	TH	RT	LT	TH	RT	LT	TH	RT	Interval	Hour	Peak
8:25	8:30	6	40	0	0	49	2	3	0	10	0	0	0	110	1126	#
8:30	8:35	2	37	0	0	37	2	10	0	21	0	0	0	109	1036	
8:35	8:40	3	40	0	0	38	7	3	0	12	0	0	0	103		
8:40	8:45	1	48	0	0	40	1	6	0	16	0	0	0	112		
8:45	8:50	0	21	0	0	38	4	5	0	18	0	0	0	86		
8:50	8:55	2	34	0	0	37	1	4	0	23	0	0	0	101		
8:55	9:00	1	27	0	0	30	3	4	0	12	0	0	0	77		
9:00	9:05	5	39	0	0	33	4	2	0	8	0	0	0	91		
9:05	9:10	3	26	0	0	37	3	4	0	21	0	0	0	94		
9:10	9:15	4	27	0	0	38	2	2	0	17	0	0	0	90		
9:15	9:20	10	26	0	0	34	0	4	0	9	0	0	0	83		
9:20	9:25	3	25	0	0	29	3	2	0	8	0	0	0	70		
9:25	9:30	7	3	0	0	6	1	0	0	3	0	0	0	20		
TOTAL		47	393	0	0	446	33	49	0	178	0	0	0	1146		
Total # of Stops		20	0	0	0	82	4	49	0	178	0	0	0	69	82	182
Average Stop Time (sec)		04.6	00.0	00.0	00.0	03.8	07.5	09.0	00.0	04.1	00.0	00.0	00.0	03.4	01.0	02.9
Average Stop Time (sec)		01.5			03.8			04.4			00.0			02.4		
Max Stop Time (sec)		15.0	00.0	00.0	00.0	12.0	16.0	35.0	00.0	21.0	00.0	00.0	00.0	35.0	12.0	21.0

Table B.5 Traffic Volume Data at Lenox Rd./Phipps Blvd.

Car Count		EB			WB			SB			NB			TEV		
Start	**End**	**LT**	**TH**	**RT**	**LT**	**TH**	**RT**	**LT**	**TH**	**RT**	**LT**	**TH**	**RT**	**Interval**	**Hour**	**Peak**
9:25	9:30	20	66	0	0	87	4	5	0	30	0	2	6	220	2072	#
9:30	9:35	21	45	0	0	64	3	1	0	21	1	0	2	158		
9:35	9:40	17	54	0	1	78	6	2	0	31	0	0	2	191		
9:40	9:45	20	60	0	2	90	5	5	0	33	1	0	2	218		
9:45	9:50	30	49	0	4	72	3	9	1	33	0	3	1	205		
9:50	9:55	20	59	0	0	80	2	4	1	31	1	0	2	200		
9:55	10:00	26	48	0	1	68	0	8	2	45	0	0	2	200		
10:00	10:05	25	45	0	2	104	4	7	0	42	0	1	2	232		
10:05	10:10	22	44	0	0	81	2	6	0	43	1	2	4	205		
10:10	10:15	20	43	0	0	82	2	9	0	24	4	0	2	186		
10:15	10:20	5	17	0	0	27	1	1	0	4	0	0	2	57		
TOTAL		226	530	0	10	833	32	57	4	337	8	8	27	2072		
Total # of Stops		176	100	0	10	349	15	54	4	255	7	8	22	247	461	292
Average Stop Time (sec)		10.4	05.0	00.0	12.2	06.7	04.5	18.4	29.7	05.1	13.6	13.1	08.8	13.6	13.6	04.6
Average Stop Time (sec)		05.1			07.8			17.8			11.8			10.6		
Max Stop Time (sec)		36.0	03.0	00.0	30.0	44.0	18.0	02.0	07.0	27.0	27.0	38.0	28.0	02.0	07.0	28.0

Table B.6 Traffic Volume Data at Spring St./17th St.

Car Count		SB			NB			EB			WB			TEV		
Start	**End**	**LT**	**TH**	**RT**	**LT**	**TH**	**RT**	**LT**	**TH**	**RT**	**LT**	**TH**	**RT**	**Interval**	**Hour**	**Peak**
10:55	11:00	5	34	4	0	0	0	0	30	11	1	12	0	97	1299	
11:00	11:05	4	30	4	0	0	0	0	32	10	1	17	0	98	1324	
11:05	11:10	2	36	2	0	0	0	0	37	9	1	19	0	106	1341	
11:10	11:15	4	35	4	0	0	0	0	30	3	6	13	0	95	1353	
11:15	11:20	6	40	10	0	0	0	0	29	12	4	16	0	117	1391	
11:20	11:25	3	21	4	0	0	0	0	38	11	4	20	0	101	1423	
11:25	11:30	5	41	6	0	0	0	0	36	10	3	18	0	119	1455	#
11:30	11:35	10	45	4	0	0	0	0	33	15	2	13	0	122	1349	
11:35	11:40	8	37	9	0	0	0	0	27	15	7	15	0	118		
11:40	11:45	0	35	1	0	0	0	0	34	8	1	16	0	95		
11:45	11:50	1	42	5	0	0	0	0	39	10	1	13	0	111		
11:50	11:55	3	32	3	0	0	0	0	42	17	2	21	0	120		
11:55	12:00	2	52	6	0	0	0	0	31	13	2	16	0	122		
12:00	12:05	7	36	4	0	0	0	0	38	10	3	17	0	115		
12:05	12:10	4	47	9	0	0	0	0	37	10	4	7	0	118		
12:10	12:15	4	49	11	0	0	0	0	42	13	3	11	0	133		
12:15	12:20	5	38	10	0	0	0	0	49	16	3	28	0	149		
12:20	12:25	3	50	6	0	0	0	0	37	9	3	25	0	133		
12:25	12:30	0	5	0	0	0	0	0	5	0	0	3	0	13		
TOTAL		76	705	102	0	0	0	0	646	202	51	300	0	2082		
Total # of Stops		46	320	42	0	0	0	0	475	121	46	280	0	92	1075	163
Average Stop Time (sec)		08.8	07.2	04.6	00.0	00.0	00.0	00.0	06.5	04.3	09.8	06.7	00.0	04.6	05.1	02.2
Average Stop Time (sec)		06.9			00.0			03.6			05.5			04.0		
Max Stop Time (sec)		17.0	30.0	18.0	00.0	00.0	00.0	00.0	51.0	40.0	41.0	41.0	00.0	41.0	51.0	40.0

Table B.7 Traffic Volume Data at W. Peachtree St./11th St.

Car Count		SB			NB			WB			EB			TEV		
Start	**End**	**LT**	**TH**	**RT**	**LT**	**TH**	**RT**	**LT**	**TH**	**RT**	**LT**	**TH**	**RT**	**Interval**	**Hour**	**Peak**
1:05	1:10	0	0	0	0	89	3	0	0	1	0	0	0	93	901	#
1:10	1:15	0	0	0	0	66	6	0	0	9	0	0	0	81	880	
1:15	1:20	0	0	0	0	65	7	0	0	3	0	0	0	75	869	
1:20	1:25	0	0	0	0	80	1	0	0	2	0	0	0	83	865	
1:25	1:30	0	0	0	0	58	5	0	0	6	0	0	0	69	858	
1:30	1:35	0	0	0	0	77	6	0	0	9	0	0	0	92	858	
1:35	1:40	0	0	0	0	60	3	0	0	2	0	0	0	65		
1:40	1:45	0	0	0	0	50	3	0	0	5	0	0	0	58		
1:45	1:50	0	0	0	2	51	5	0	0	4	0	0	0	62		
1:50	1:55	0	0	0	0	55	6	0	0	3	0	0	0	64		
1:55	2:00	0	0	0	1	71	4	0	0	3	0	0	0	79		
2:00	2:05	0	0	0	2	63	4	0	0	11	0	0	0	80		
2:05	2:10	0	0	0	0	59	6	0	0	7	0	0	0	72		
2:10	2:15	0	0	0	2	60	1	0	0	7	0	0	0	70		
2:15	2:20	0	0	0	1	63	5	0	0	2	0	0	0	71		
2:20	2:25	0	0	0	0	64	3	0	0	9	0	0	0	76		
2:25	2:30	0	0	0	1	62	1	0	0	5	0	0	0	69		
TOTAL		0	0	0	9	1093	69	0	0	88	0	0	0	1259		
Total # of Stops		0	0	0	0	8	1	0	0	88	0	0	0	0	8	89
Average Stop Time (sec)		00.0	00.0	00.0	00.0	02.9	07.0	00.0	00.0	05.8	00.0	00.0	00.0	00.0	00.7	03.2
Average Stop Time (sec)		00.0			03.3			01.9			00.0			01.3		
Max Stop Time (sec)		00.0	00.0	00.0	00.0	04.0	07.0	00.0	00.0	37.0	00.0	00.0	00.0	00.0	04.0	37.0

Table B.8 Traffic Volume Data at W. Peachtree St./16th St.

Car Count		NB			SB			EB			WB			TEV		
Start	**End**	**LT**	**TH**	**RT**	**LT**	**TH**	**RT**	**LT**	**TH**	**RT**	**LT**	**TH**	**RT**	**Interval**	**Hour**	**Peak**
3:30	3:35	8	112	0	0	0	0	21	0	0	0	0	0	141	1697	#
3:35	3:40	14	121	0	0	0	0	17	0	0	0	0	0	152	1566	
3:40	3:45	6	103	0	0	0	0	12	0	0	0	0	0	121		
3:45	3:50	5	131	0	0	0	0	12	0	0	0	0	0	148		
3:50	3:55	8	131	0	0	0	0	22	0	0	0	0	0	161		
3:55	4:00	8	137	0	0	0	0	19	0	0	0	0	0	164		
4:00	4:05	7	109	0	0	0	0	18	0	0	0	0	0	134		
4:05	4:10	9	109	0	0	0	0	19	0	0	0	0	0	137		
4:10	4:15	7	102	0	0	0	0	20	0	0	0	0	0	129		
4:15	4:20	6	111	0	0	0	0	21	1	0	0	0	0	139		
4:20	4:25	4	115	0	0	0	0	13	0	0	0	0	0	132		
4:25	4:30	8	116	0	0	0	0	15	0	0	0	0	0	139		
4:30	4:35	1	7	0	0	0	0	2	0	0	0	0	0	10		
TOTAL		91	1404	0	0	0	0	211	1	0	0	0	0	1707		
Total # of Stops		39	120	0	0	0	0	196	1	0	0	0	0	235	121	0
Average Stop Time (sec)		05.8	04.8	00.0	00.0	00.0	00.0	09.8	02.0	00.0	00.0	00.0	00.0	03.9	01.7	00.0
Average Stop Time (sec)		03.5			00.0			03.9			00.0			01.9		
Max Stop Time (sec)		31.0	15.0	00.0	00.0	00.0	00.0	22.0	02.0	00.0	00.0	00.0	00.0	22.0	15.0	00.0

Table B.9 Traffic Volume Data at 14th St./Williams St.

Car Count		EB			WB			NB			SB			TEV		
Start	**End**	**LT**	**TH**	**RT**	**LT**	**TH**	**RT**	**LT**	**TH**	**RT**	**LT**	**TH**	**RT**	**Interval**	**Hour**	**Peak**
1:20	1:25	13	65	0	0	32	8	20	32	17	0	0	0	187	2400	#
1:25	1:30	14	58	0	0	34	10	16	26	22	0	0	0	180	2223	
1:30	1:35	11	62	0	0	43	13	16	38	24	0	0	0	207		
1:35	1:40	12	67	0	0	39	8	22	38	19	0	0	0	205		
1:40	1:45	17	62	0	0	42	9	17	32	21	0	0	0	200		
1:45	1:50	20	68	0	0	32	11	22	33	23	0	0	0	209		
1:50	1:55	11	53	0	0	36	16	20	37	29	0	0	0	202		
1:55	2:00	15	63	0	0	48	11	17	38	21	0	0	0	213		
2:00	2:05	11	64	0	0	37	12	23	32	22	0	0	0	201		
2:05	2:10	14	66	0	0	45	14	13	43	23	0	0	0	218		
2:10	2:15	9	53	0	0	52	20	17	26	21	0	0	0	198		
2:15	2:20	11	52	0	0	39	14	16	24	24	0	0	0	180		
2:20	2:25	0	4	0	0	2	0	0	0	4	0	0	0	10		
TOTAL		158	737	0	0	481	146	219	399	270	0	0	0	2410		
Total # of Stops		69	515	0	0	212	75	178	304	170	0	0	0	247	1031	245
Average Stop Time (sec)		08.4	08.6	00.0	00.0	05.6	05.5	10.6	10.3	09.0	00.0	00.0	00.0	04.7	06.1	03.6
Average Stop Time (sec)		05.7			03.7			10.0			00.0			04.8		
Max Stop Time (sec)		22.0	44.0	00.0	00.0	20.0	16.0	38.0	47.0	39.0	00.0	00.0	00.0	38.0	47.0	39.0

Table B.10 Traffic Volume Data at Market St./16th St.

Car Count		NB			SB			WB			EB			TEV		
Start	**End**	**LT**	**TH**	**RT**	**LT**	**TH**	**RT**	**LT**	**TH**	**RT**	**LT**	**TH**	**RT**	**Interval**	**Hour**	**Peak**
2:30	2:35	0	22	0	3	16	0	0	0	0	0	0	0	41	459	#
2:35	2:40	0	28	1	0	13	0	1	0	0	0	0	0	43	429	
2:40	2:45	0	29	3	1	11	0	0	0	0	0	0	0	44		
2:45	2:50	0	20	1	0	20	0	2	0	0	0	0	0	43		
2:50	2:55	0	17	0	1	9	0	1	0	0	0	0	0	28		
2:55	3:00	0	20	3	1	12	0	1	0	1	0	0	0	38		
3:00	3:05	0	15	1	0	12	0	0	0	0	0	0	0	28		
3:05	3:10	0	28	2	1	17	0	3	0	0	0	0	0	51		
3:10	3:15	0	16	4	0	9	0	0	0	0	0	0	0	29		
3:15	3:20	0	27	1	0	13	0	1	0	1	0	0	0	43		
3:20	3:25	0	15	2	0	17	0	1	0	0	0	0	0	35		
3:25	3:30	0	17	5	1	11	0	0	0	2	0	0	0	36		
3:30	3:35	0	7	0	0	4	0	0	0	0	0	0	0	11		
TOTAL		0	261	23	8	164	0	10	0	4	0	0	0	470		
Total # of Stops		0	56	5	3	14	0	10	0	3	0	0	0	13	70	8
Average Stop Time (sec)		00.0	03.8	05.2	06.7	03.1	00.0	04.9	00.0	03.7	00.0	00.0	00.0	02.9	01.7	02.2
Average Stop Time (sec)		03.0			03.2			02.9			00.0			02.3		
Max Stop Time (sec)		00.0	18.0	11.0	10.0	07.0	00.0	08.0	00.0	06.0	00.0	00.0	00.0	10.0	18.0	11.0

Table B.11 Traffic Volume Data at 17th St./Bishop St.

Car Count		WB			EB			SB			NB			TEV		
Start	**End**	**LT**	**TH**	**RT**	**LT**	**TH**	**RT**	**LT**	**TH**	**RT**	**LT**	**TH**	**RT**	**Interval**	**Hour**	**Peak**
5:00	5:05	1	25	1	5	17	0	2	0	15	0	0	0	66	822	#
5:05	5:10	2	31	5	9	28	0	3	0	16	0	0	0	94		
5:10	5:15	1	31	1	7	15	0	4	0	19	0	0	0	78		
5:15	5:20	1	24	2	14	31	0	3	0	17	0	0	0	92		
5:20	5:25	1	26	4	8	24	0	2	0	37	0	0	0	102		
5:25	5:30	1	35	2	15	23	0	4	0	33	0	0	0	113		
5:30	5:35	0	29	1	5	21	0	2	0	20	0	0	0	78		
5:35	5:40	3	35	4	9	24	0	2	0	18	0	0	0	95		
5:40	5:45	0	33	0	11	25	0	2	0	13	0	0	0	84		
5:45	5:50	0	10	1	3	4	0	0	0	2	0	0	0	20		
TOTAL		10	279	21	86	212	0	24	0	190	0	0	0	822		
Total # of Stops		4	11	1	29	3	0	17	0	103	0	0	0	50	14	104
Average Stop Time (sec)		09.0	04.8	02.0	06.1	04.7	00.0	09.2	00.0	03.8	00.0	00.0	00.0	06.1	02.4	01.4
Average Stop Time (sec)		05.3			03.6			04.3			00.0			03.3		
Max Stop Time (sec)		17.0	08.0	02.0	15.0	11.0	00.0	32.0	00.0	22.0	00.0	00.0	00.0	32.0	11.0	22.0

Table B.12 Traffic Volume Data at Piedmont Rd./The Prado

Car Count		NB			SB			EB			WB			TEV		
Start	**End**	**LT**	**TH**	**RT**	**LT**	**TH**	**RT**	**LT**	**TH**	**RT**	**LT**	**TH**	**RT**	**Interval**	**Hour**	**Peak**
5:35	5:40	4	110	1	0	72	4	13	0	2	0	1	2	209	2192	#
5:40	5:45	6	101	4	0	76	4	22	0	1	1	1	2	218		
5:45	5:50	4	83	0	0	69	1	25	0	2	0	1	2	187		
5:50	5:55	4	88	0	1	72	5	19	0	3	1	0	0	193		
5:55	6:00	7	79	0	1	67	2	28	0	2	0	1	1	188		
6:00	6:05	2	108	0	4	83	4	16	0	1	0	2	4	224		
6:05	6:10	3	102	0	0	67	6	21	0	2	1	0	1	203		
6:10	6:15	5	97	0	1	69	10	23	0	2	0	0	1	208		
6:15	6:20	7	103	0	0	84	6	20	0	3	0	0	0	223		
6:20	6:25	4	98	0	1	80	5	25	0	2	0	0	0	215		
6:25	6:30	2	53	0	0	46	3	17	0	1	0	0	2	124		
TOTAL		48	1022	5	8	785	50	229	0	21	3	6	15	2192		
Total # of Stops		45	859	4	5	682	30	224	0	20	3	6	15	277	1547	69
Average Stop Time (sec)		07.3	04.1	03.2	08.4	04.8	02.4	05.7	00.0	04.7	07.7	06.5	07.7	07.3	03.9	04.5
Average Stop Time (sec)		04.9			05.2			03.4			07.3			05.2		
Max Stop Time (sec)		19.0	17.0	07.0	13.0	22.0	05.0	11.0	00.0	15.0	13.0	14.0	12.0	11.0	22.0	15.0

Table B.13 Traffic Volume Data at Roswell Rd./W. Wieuca Rd.

Car Count		NB			SB			WB			EB			TEV		
Start	**End**	**LT**	**TH**	**RT**	**LT**	**TH**	**RT**	**LT**	**TH**	**RT**	**LT**	**TH**	**RT**	**Interval**	**Hour**	**Peak**
11:20	11:25	4	56	2	11	65	5	0	9	17	10	10	12	201	2523	#
11:25	11:30	6	46	3	7	61	1	0	11	10	9	9	20	183	2439	
11:30	11:35	3	59	2	10	72	5	4	5	11	13	6	23	213		
11:35	11:40	11	69	0	12	67	3	2	10	14	6	7	16	217		
11:40	11:45	9	65	1	15	67	2	0	7	9	9	7	12	203		
11:45	11:50	9	61	1	13	64	3	0	13	16	9	8	21	218		
11:50	11:55	7	68	0	11	62	4	3	7	9	9	9	28	217		
11:55	12:00	5	72	1	12	68	2	4	9	16	14	0	21	224		
12:00	12:05	4	48	1	18	64	9	4	7	18	9	7	9	198		
12:05	12:10	9	62	1	14	56	2	3	5	18	10	9	20	209		
12:10	12:15	8	57	1	9	66	4	3	8	19	9	15	13	212		
12:15	12:20	8	77	1	6	78	5	2	9	14	3	9	16	228		
12:20	12:25	5	37	1	7	39	1	1	5	4	3	4	10	117		
TOTAL		88	777	15	145	829	46	26	105	175	113	100	221	2640		
Total # of Stops		70	626	13	134	716	27	18	61	115	109	93	199	331	1496	354
Average Stop Time (sec)		08.9	07.3	05.5	10.2	06.7	04.9	08.4	07.7	06.3	11.3	09.4	07.0	09.7	07.8	05.9
Average Stop Time (sec)		07.2			07.2			07.5			09.2			07.8		
Max Stop Time (sec)		32.0	55.0	09.0	43.0	23.0	15.0	18.0	28.0	27.0	02.0	28.0	30.0	02.0	55.0	30.0

APPENDIX C

ONE- AND FIVE-MINUTE MAJOR STREET VEHICLE STOPS AT YELLOW/RED FLASHING SIGNALS

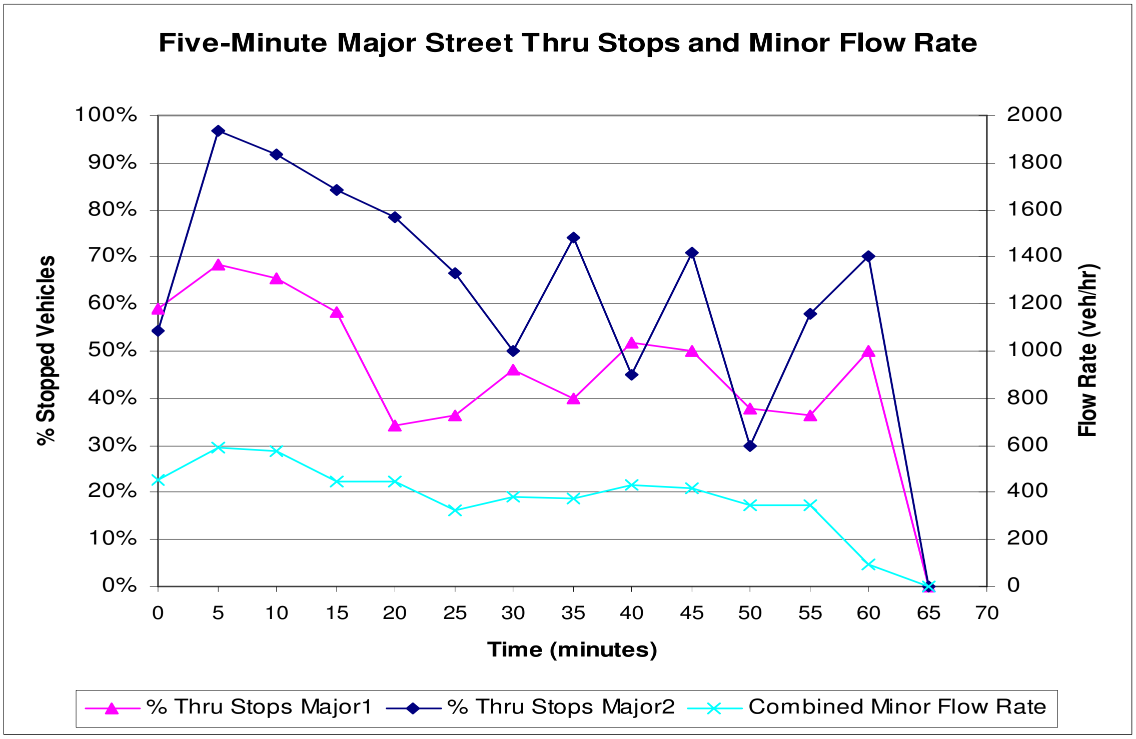


Figure C.1 Five-Minute Major Street Vehicle Stops at Northside Dr./Peachtree Battle Ave.

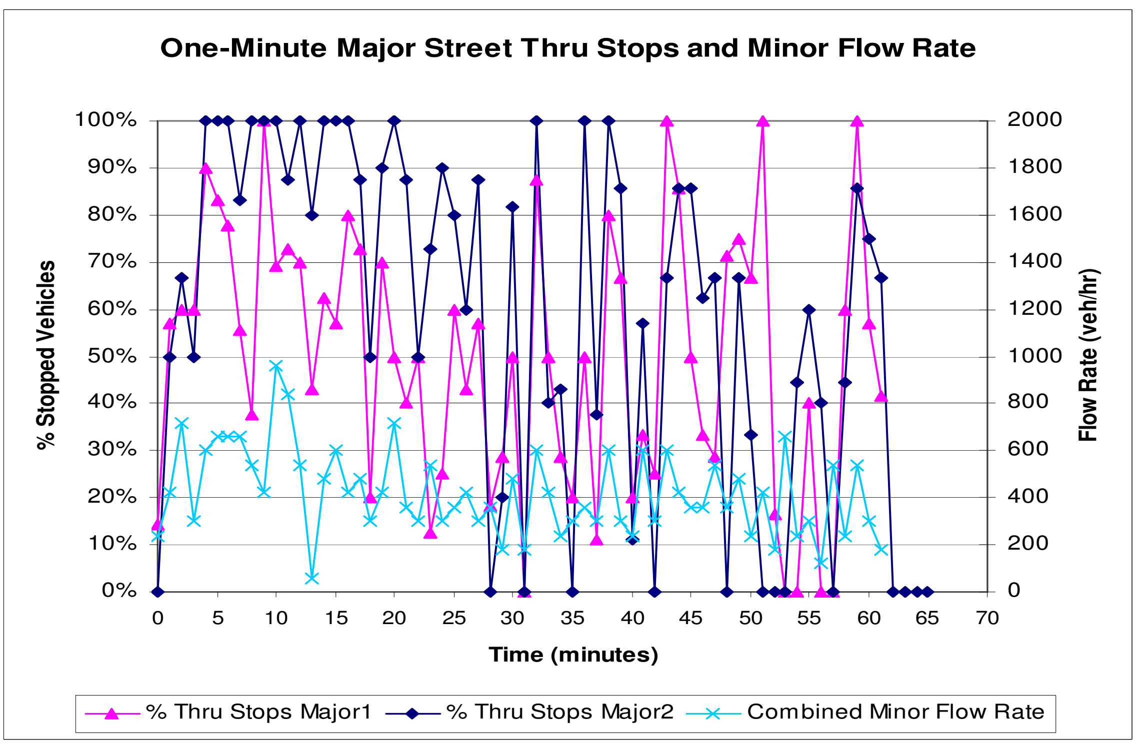


Figure C.2 One-Minute Major Street Vehicle Stops at Northside Dr./Peachtree Battle Ave.

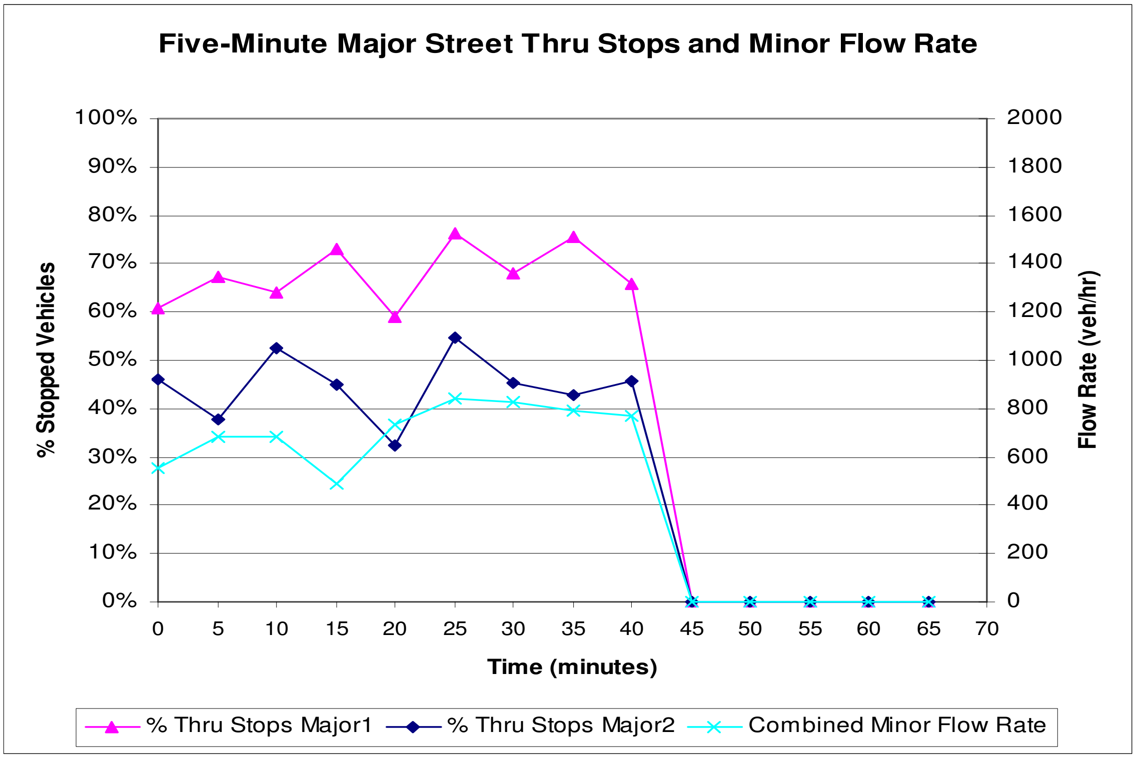


Figure C.3 Five-Minute Major Street Vehicle Stops at Monroe Dr./10th St.

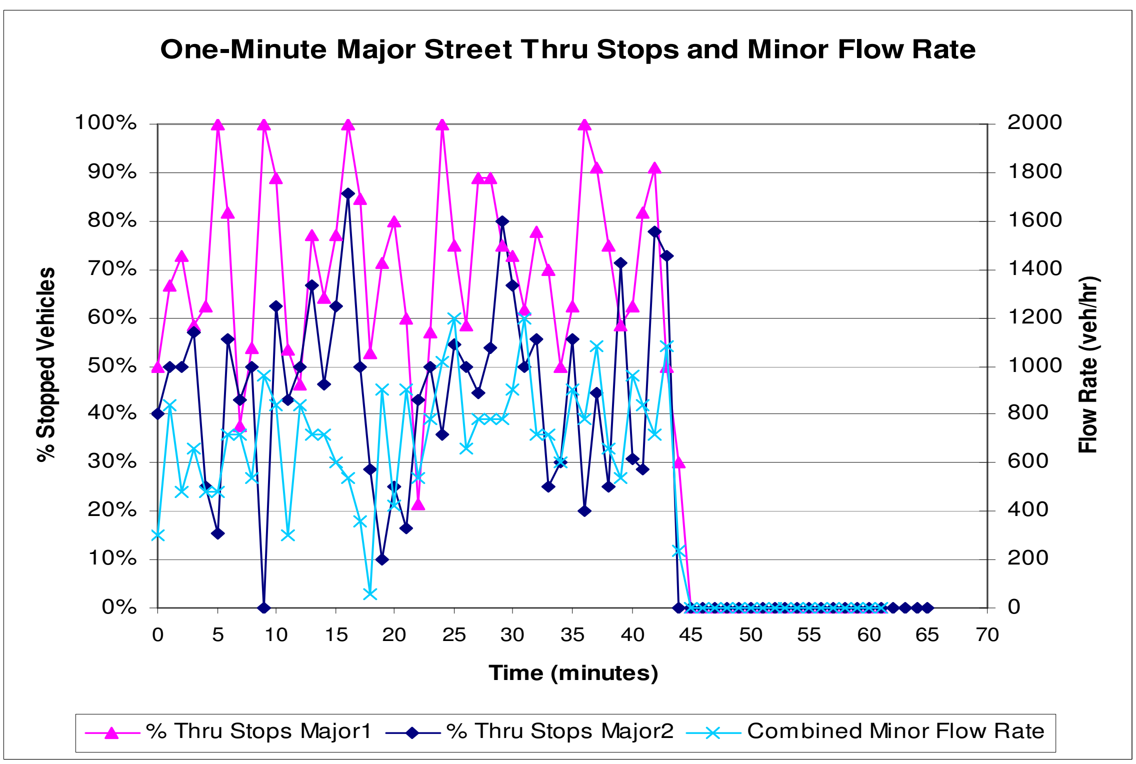


Figure C.4 One-Minute Major Street Vehicle Stops at Monroe Dr./10th St.

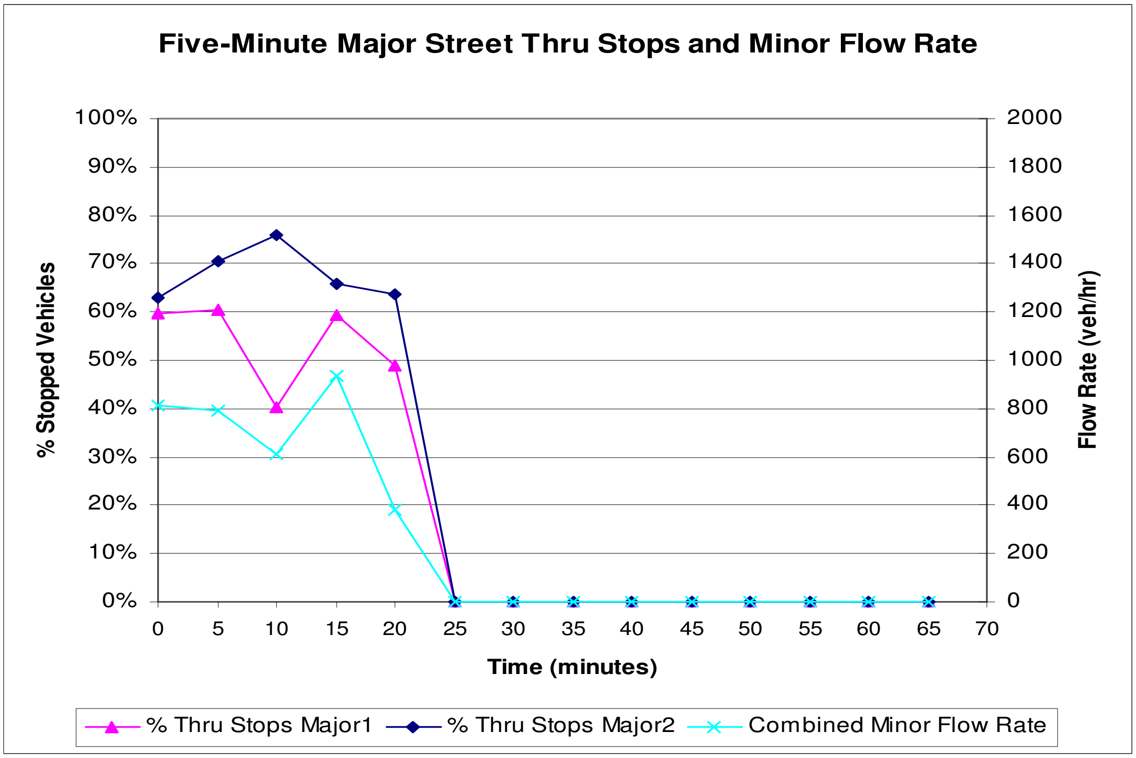


Figure C.5 Five-Minute Major Street Vehicle Stops at Rainbow St./Candler Dr.

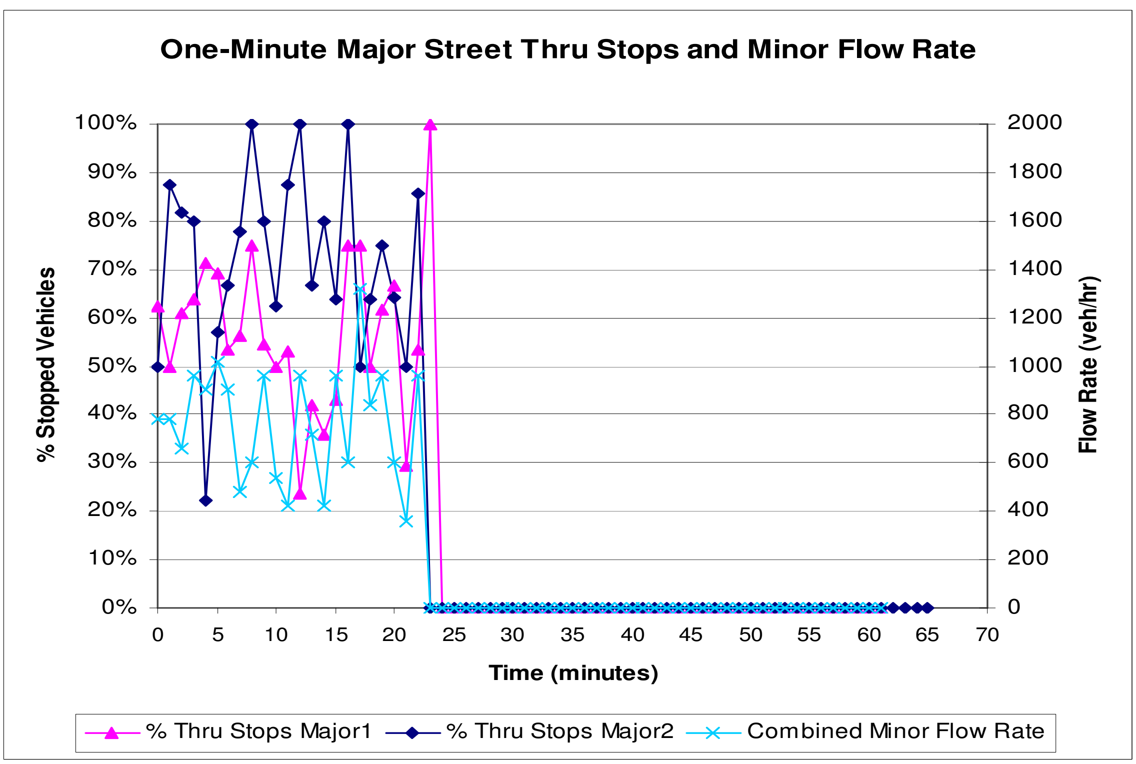


Figure C.6 One-Minute Major Street Vehicle Stops at Rainbow St./Candler Dr.

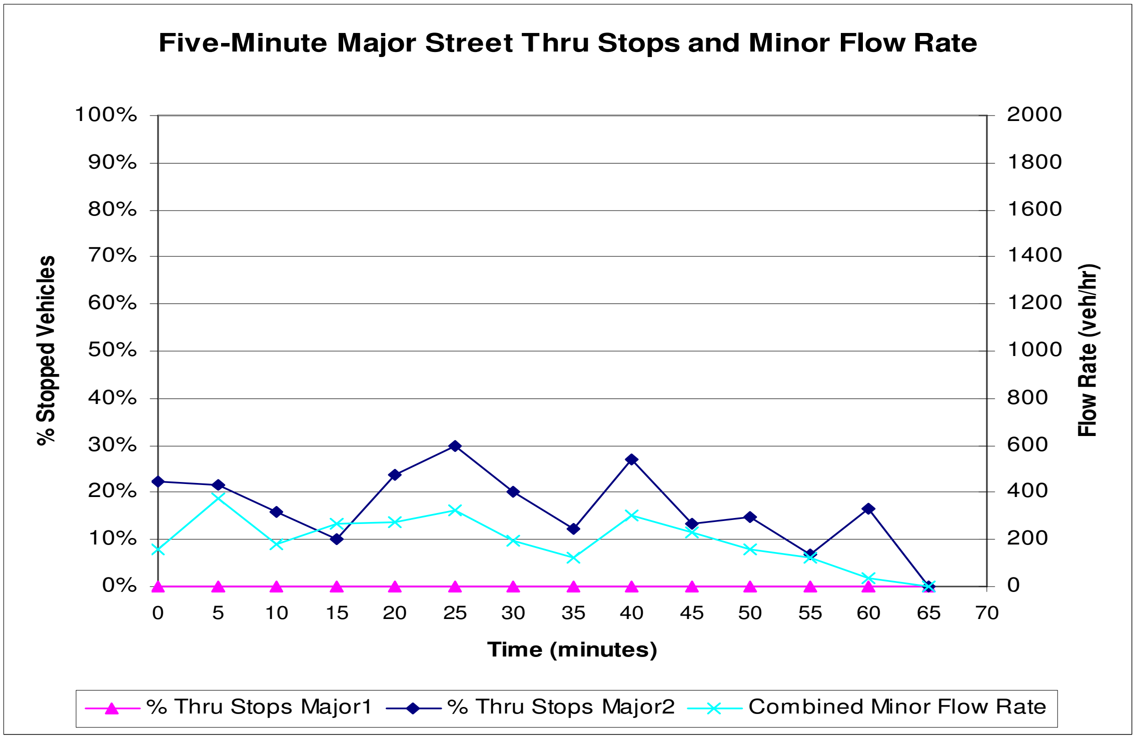


Figure C.7 Five-Minute Major Street Vehicle Stops at N. Highland Ave./University Dr.

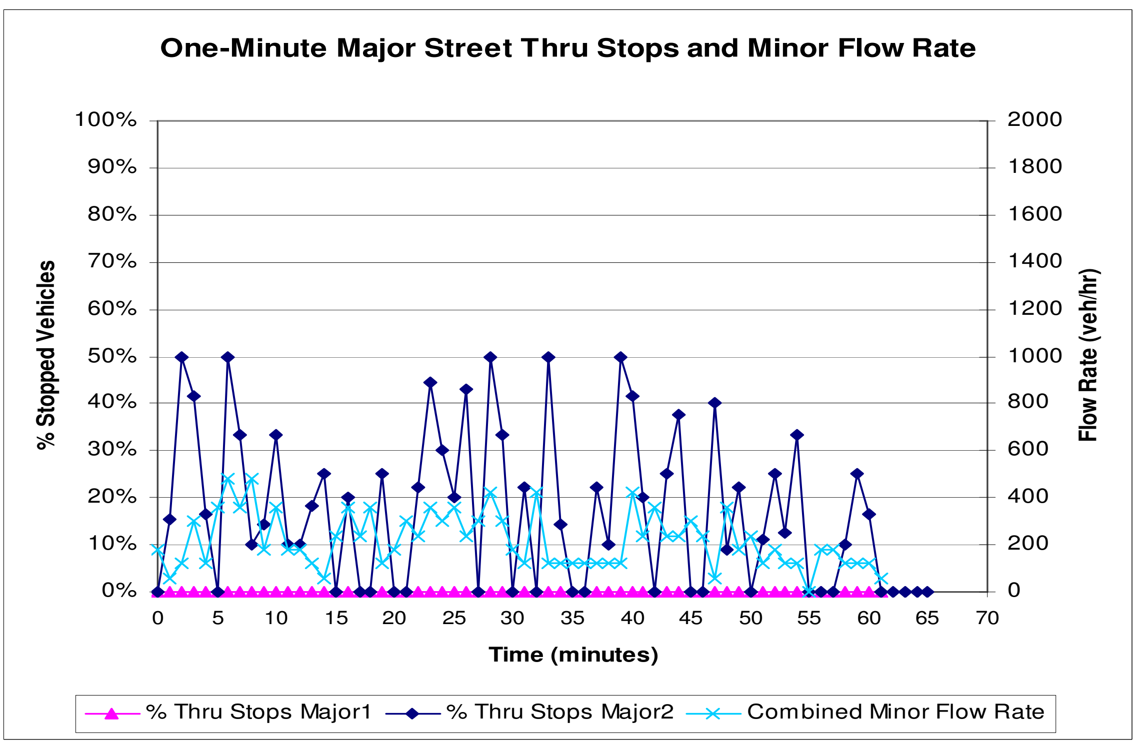


Figure C.8 One-Minute Major Street Vehicle Stops at N. Highland Ave./University Dr.

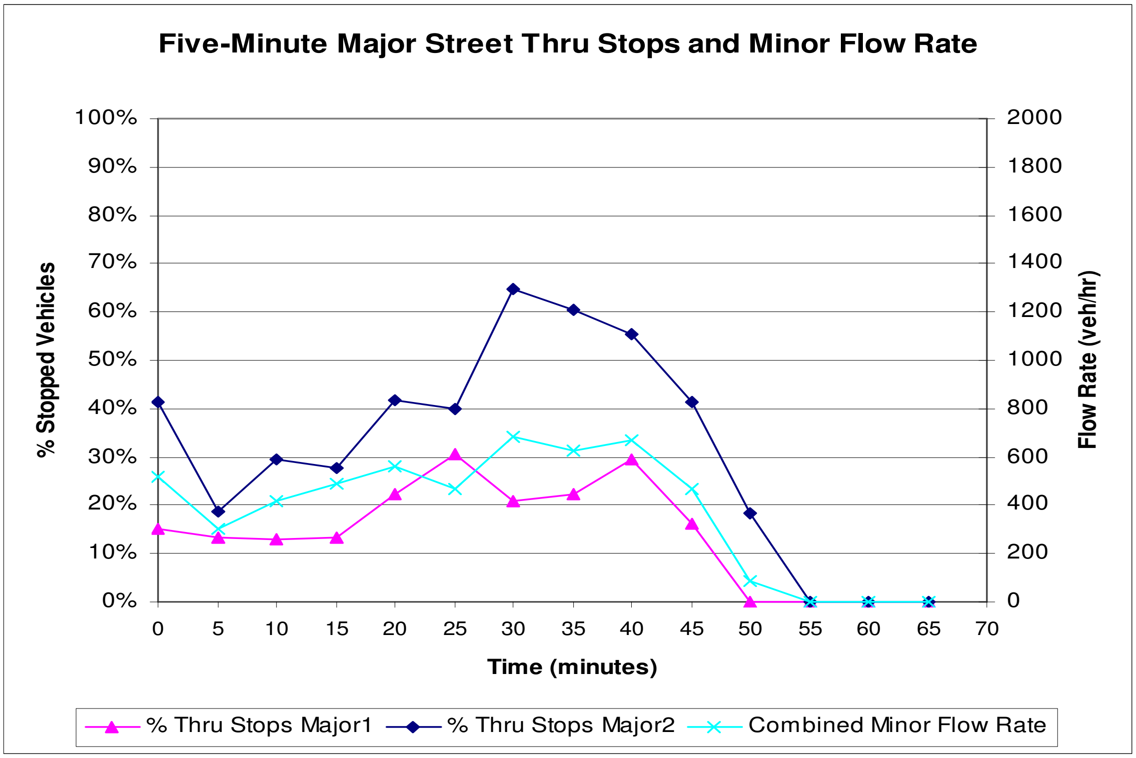


Figure C.9 Five-Minute Major Street Vehicle Stops at Lenox Rd./Phipps Blvd.

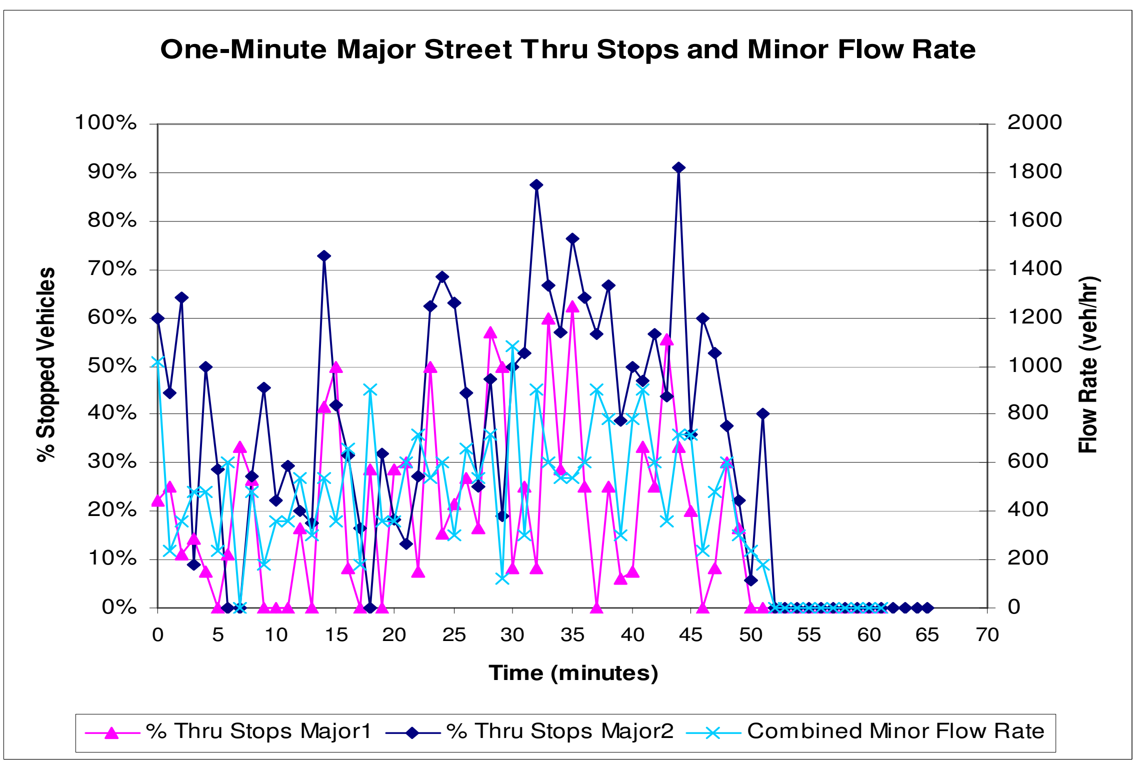


Figure C.10 One-Minute Major Street Vehicle Stops at Lenox Rd./Phipps Blvd.

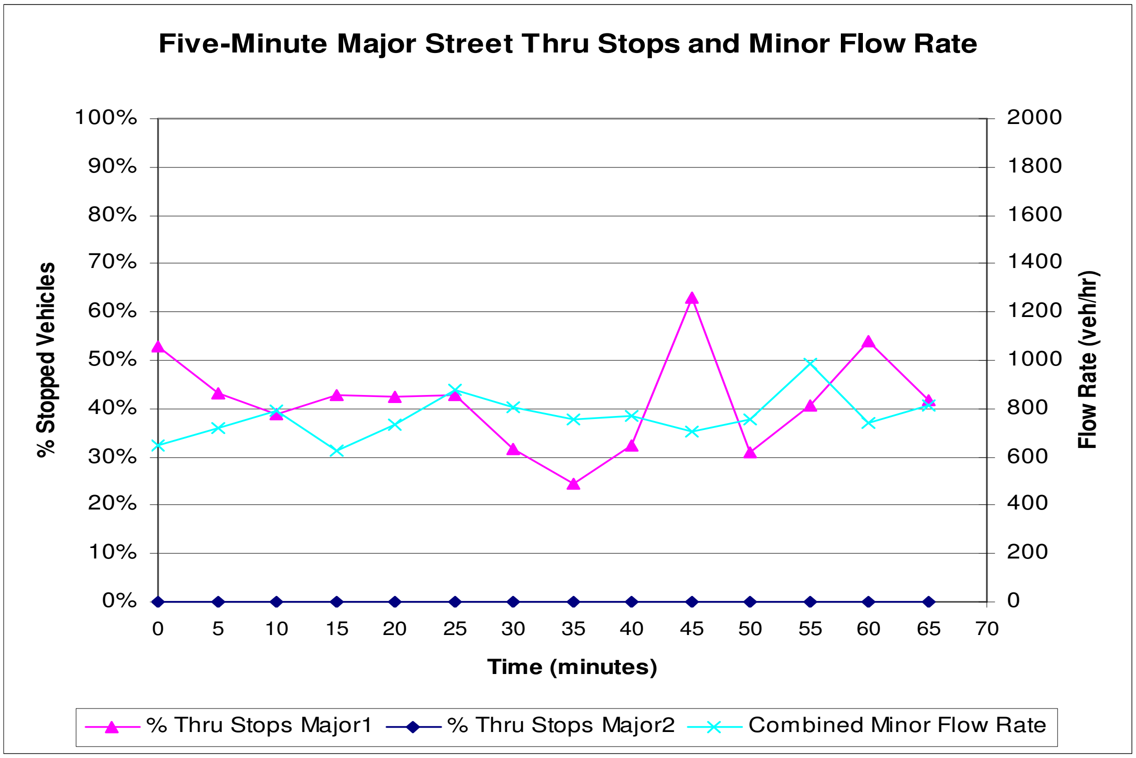


Figure C.11 Five-Minute Major Street Vehicle Stops at Spring St./17th St.

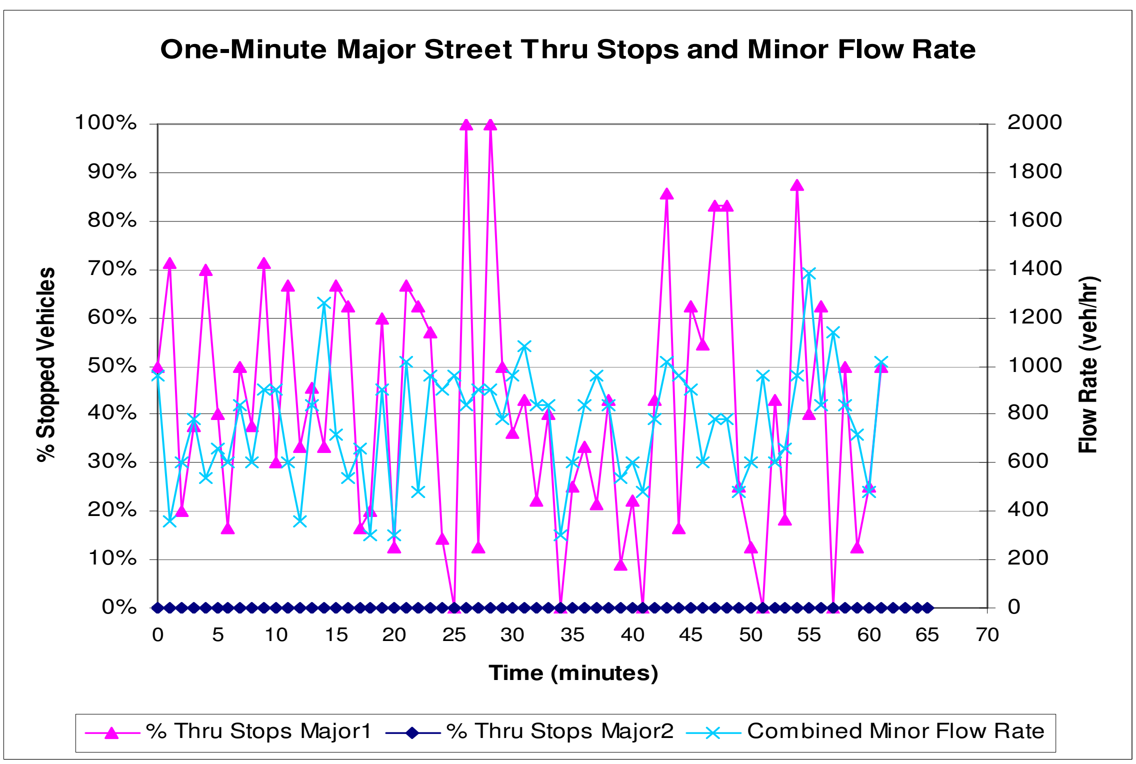


Figure C.12 One-Minute Major Street Vehicle Stops at Spring St./17th St.

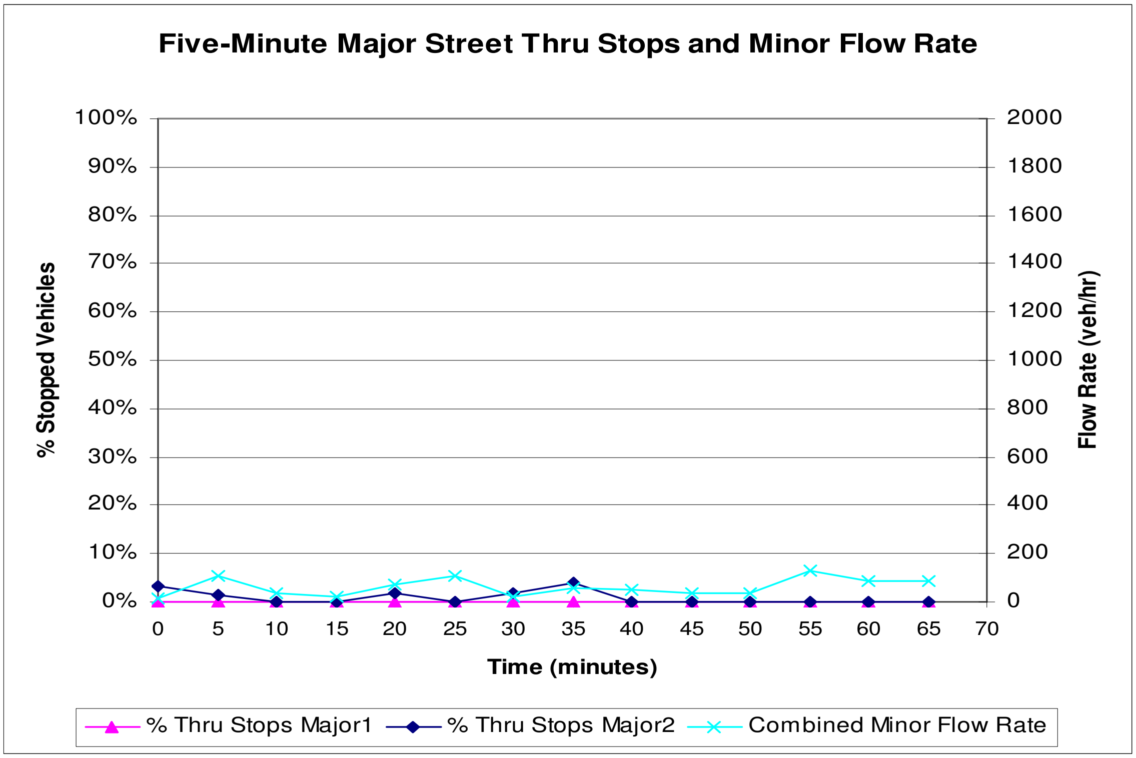


Figure C.13 Five-Minute Major Street Vehicle Stops at W. Peachtree St./11th St.

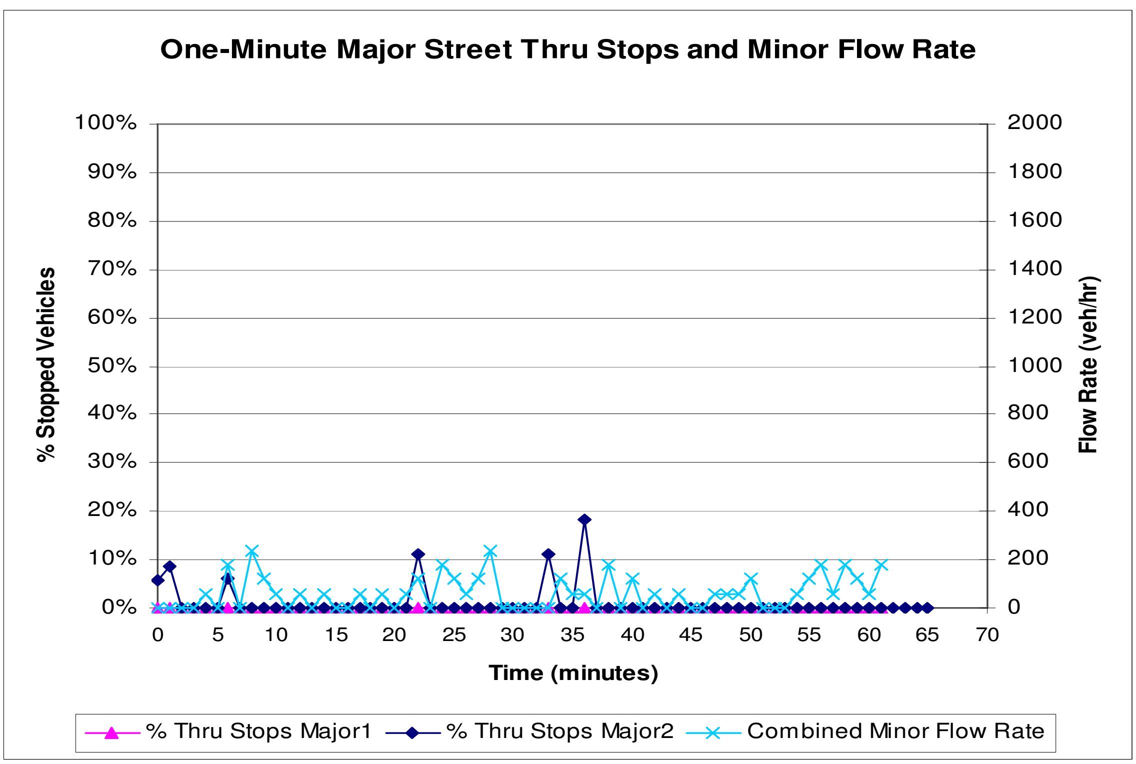


Figure C.14 One-Minute Major Street Vehicle Stops at W. Peachtree St./11th St.

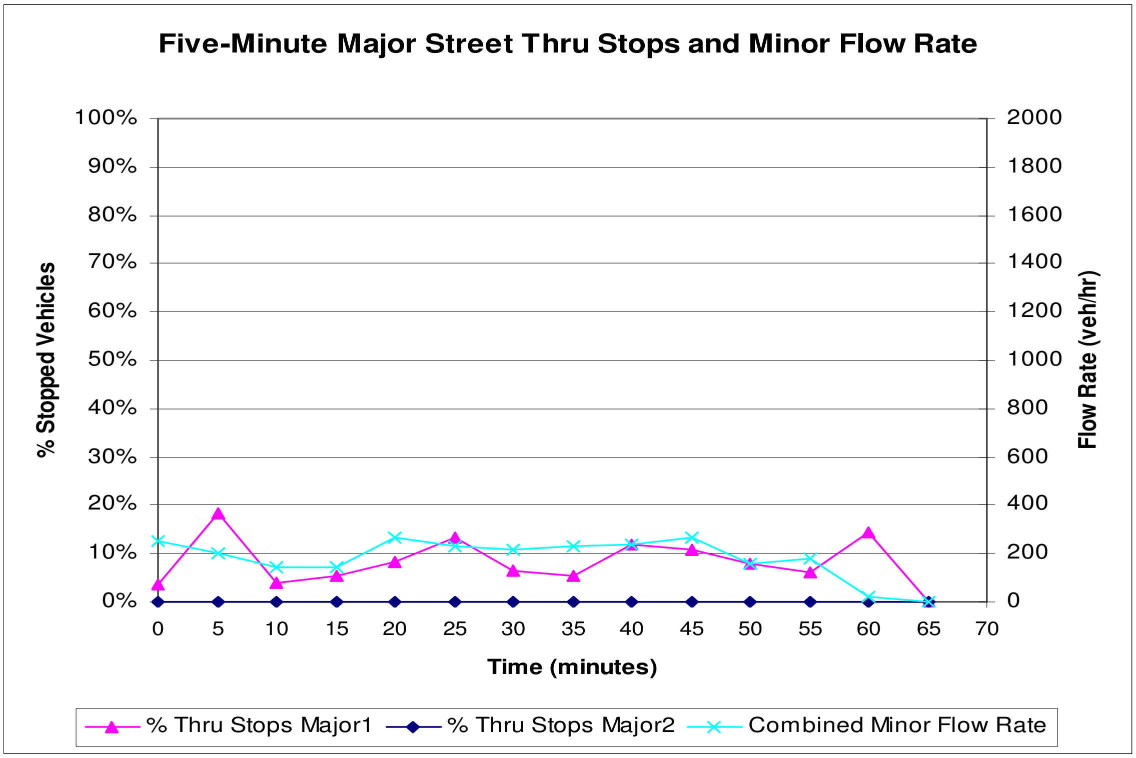


Figure C.15 Five-Minute Major Street Vehicle Stops at W. Peachtree St./16th St.

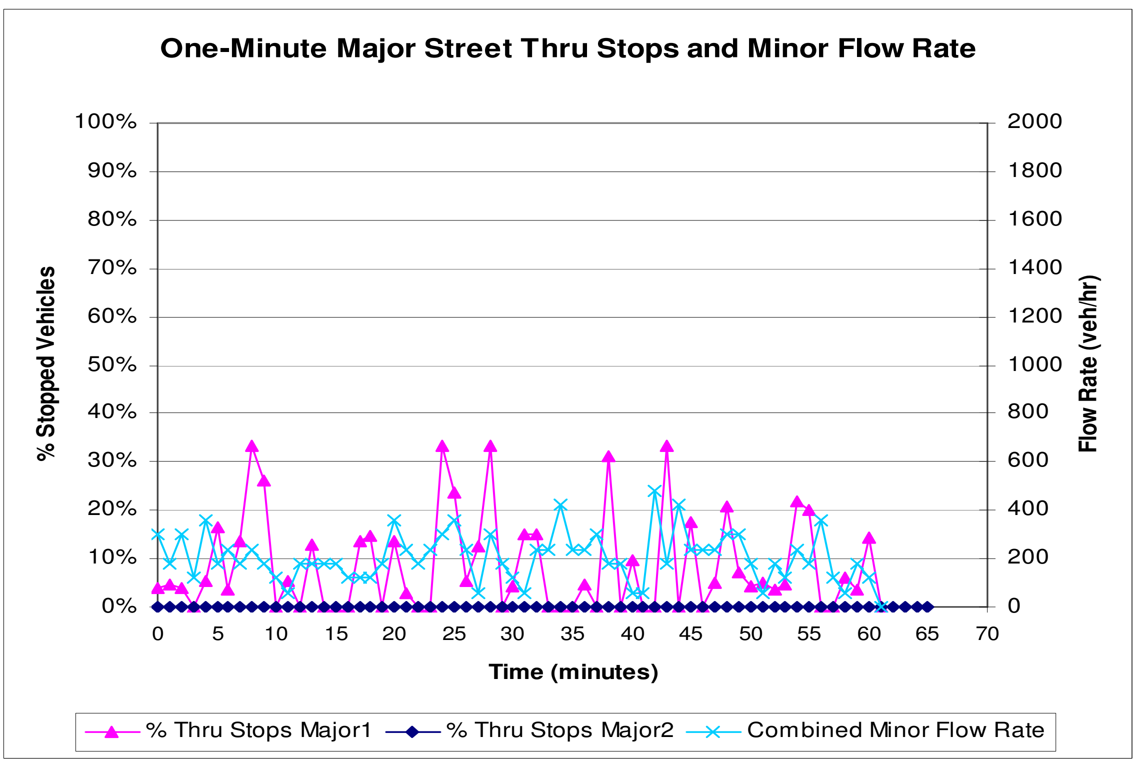


Figure C.16 One-Minute Major Street Vehicle Stops at W. Peachtree St./16th St.

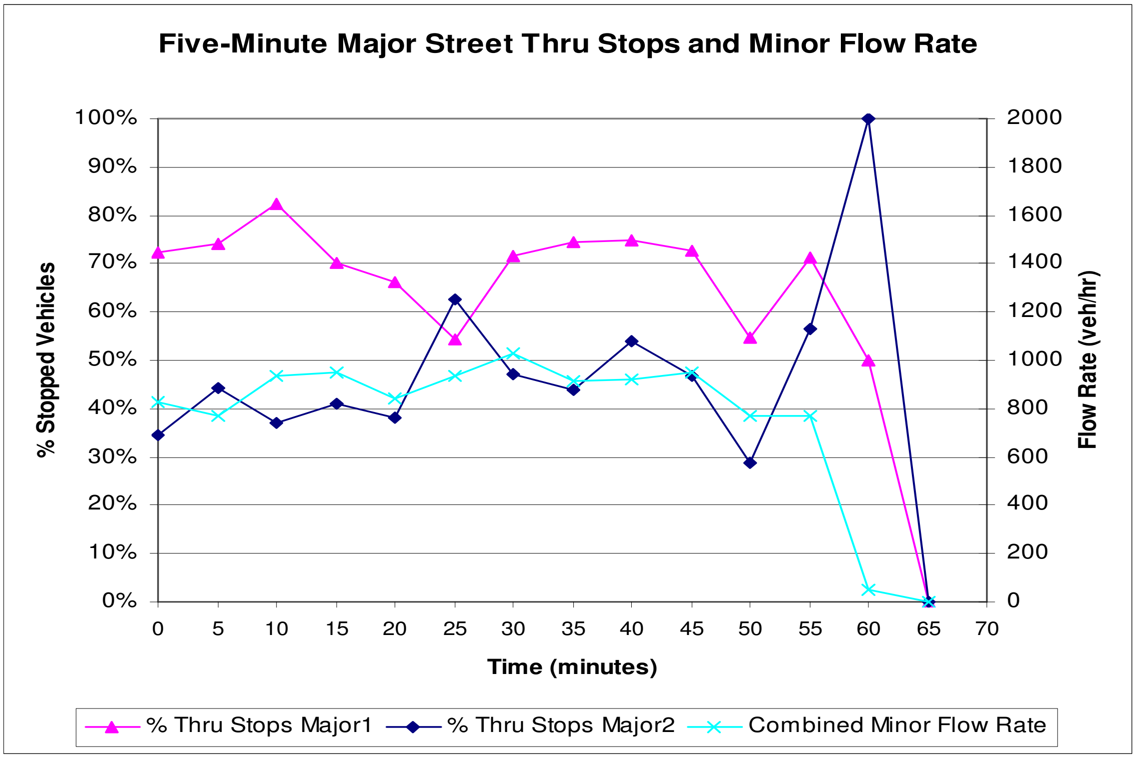


Figure C.17 Five-Minute Major Street Vehicle Stops at 14th St./Williams St.

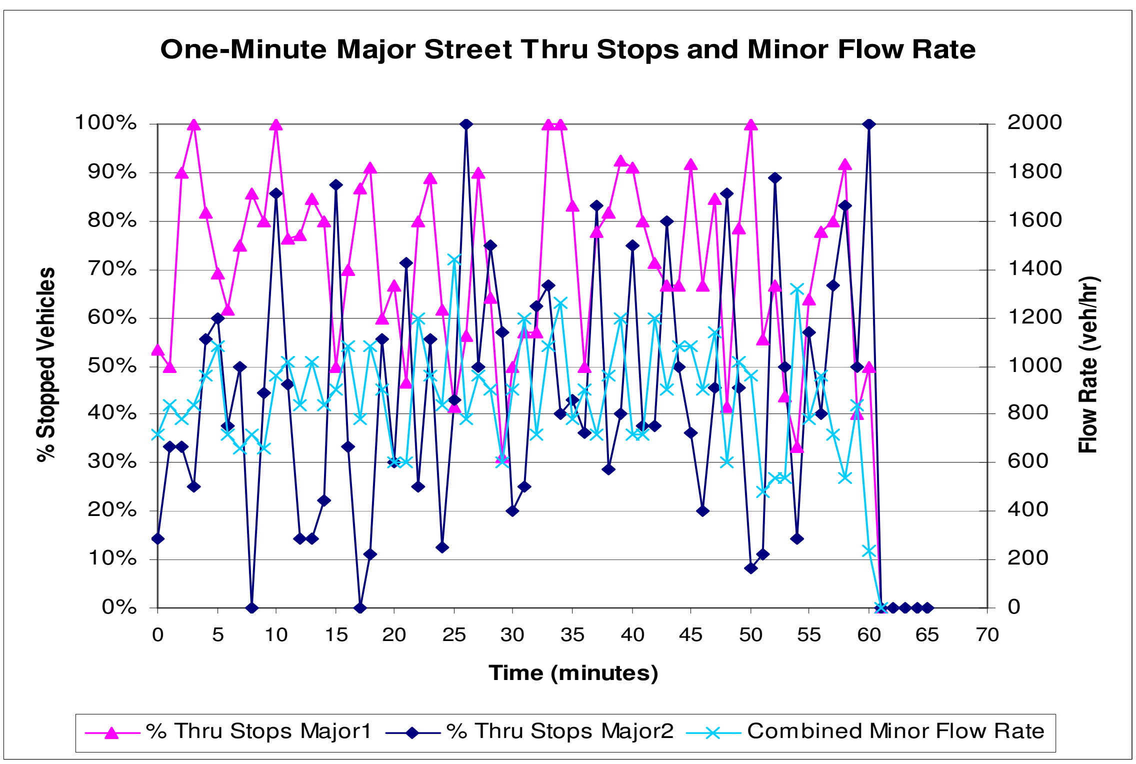


Figure C.18 One-Minute Major Street Vehicle Stops at 14th St./Williams St.

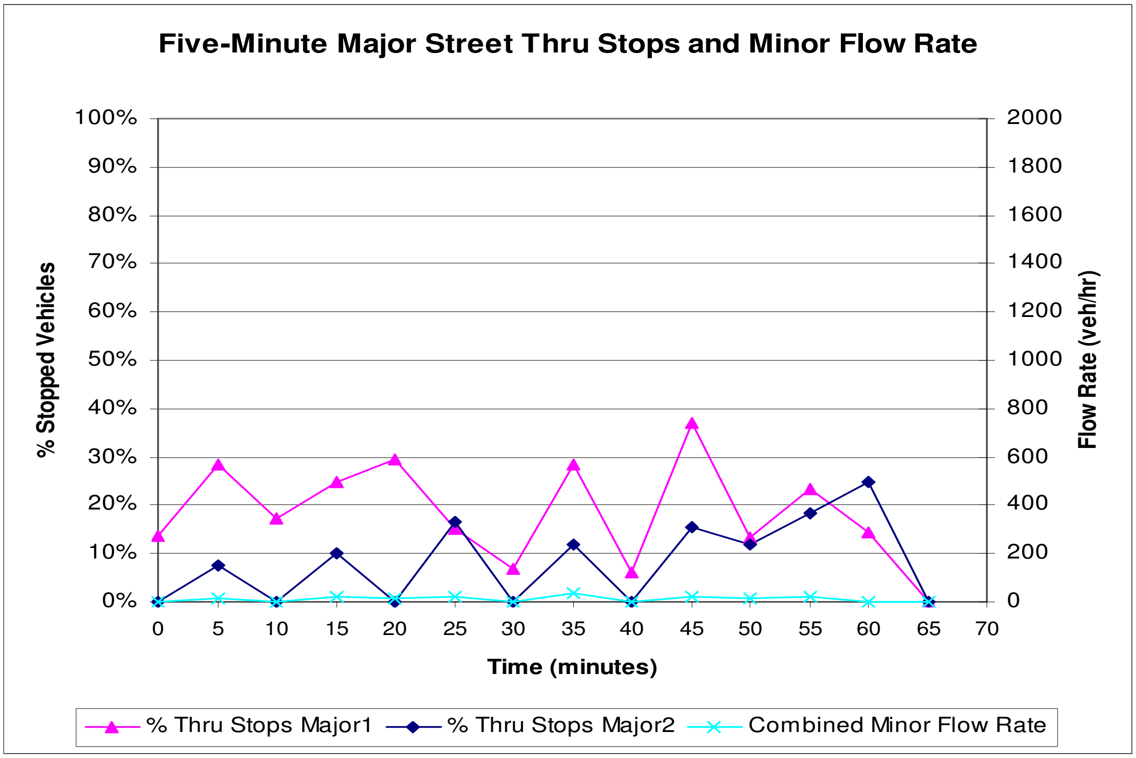


Figure C.19 Five-Minute Major Street Vehicle Stops at Market St./16th St.

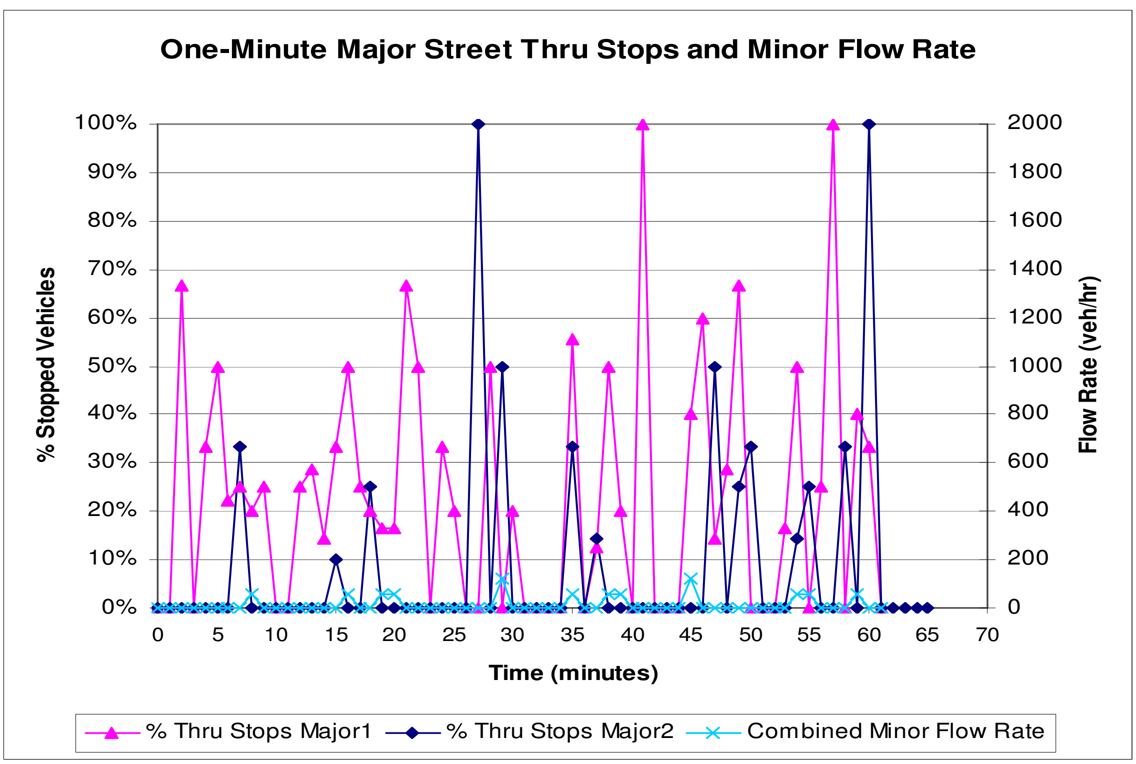


Figure C.20 One-Minute Major Street Vehicle Stops at Market St./16th St.

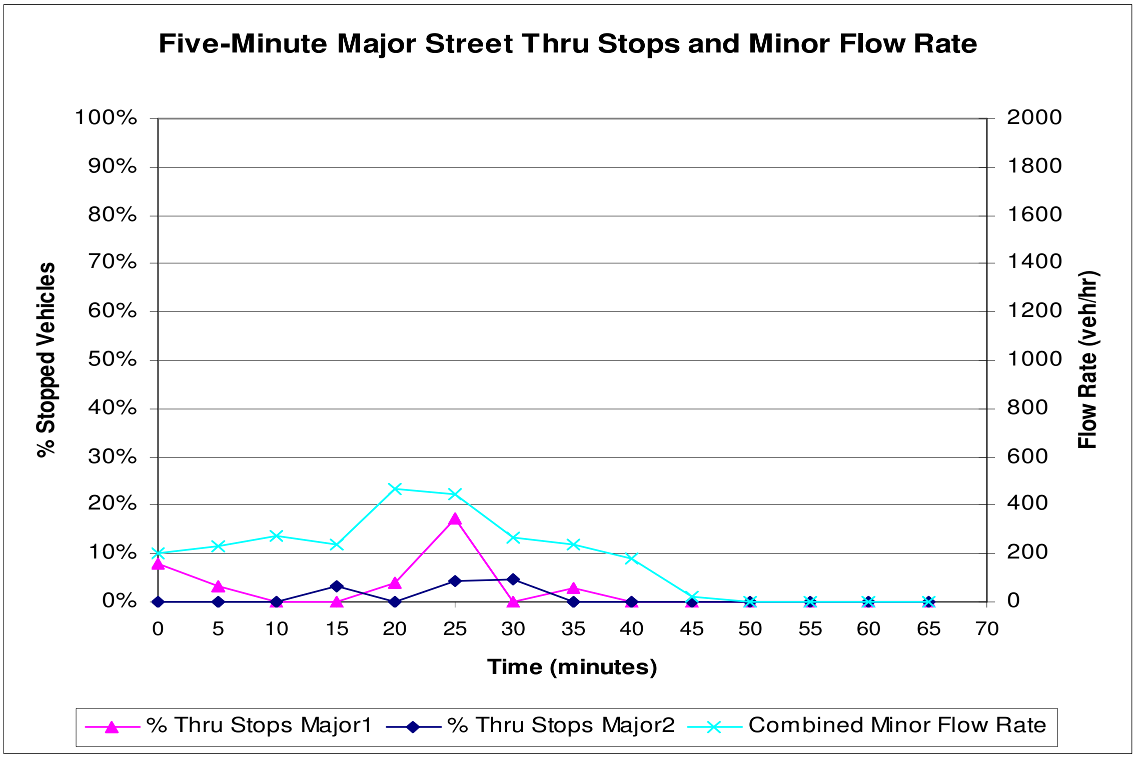


Figure C.21 Five-Minute Major Street Vehicle Stops at 17th St./Bishop St.

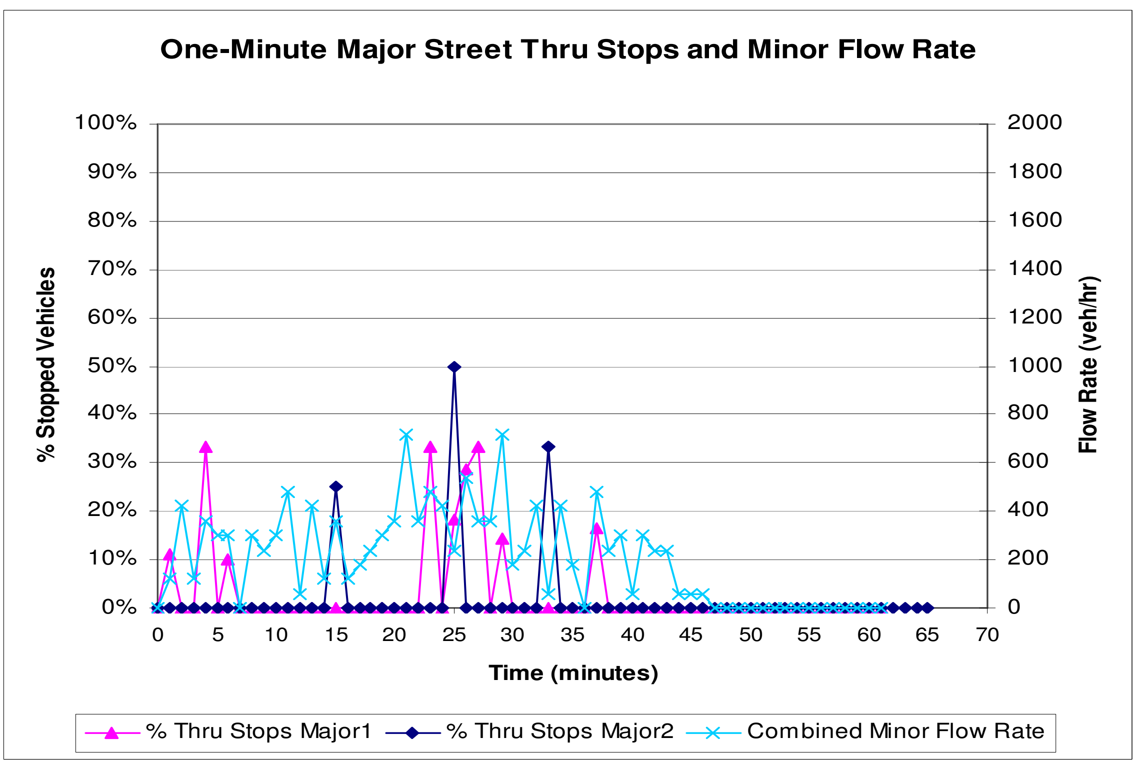


Figure C.22 One-Minute Major Street Vehicle Stops at 17th St./Bishop St.

APPENDIX D

ONE- AND FIVE-MINUTE MAJOR STREET VEHICLE STOPS AT RED/RED FLASHING SIGNALS

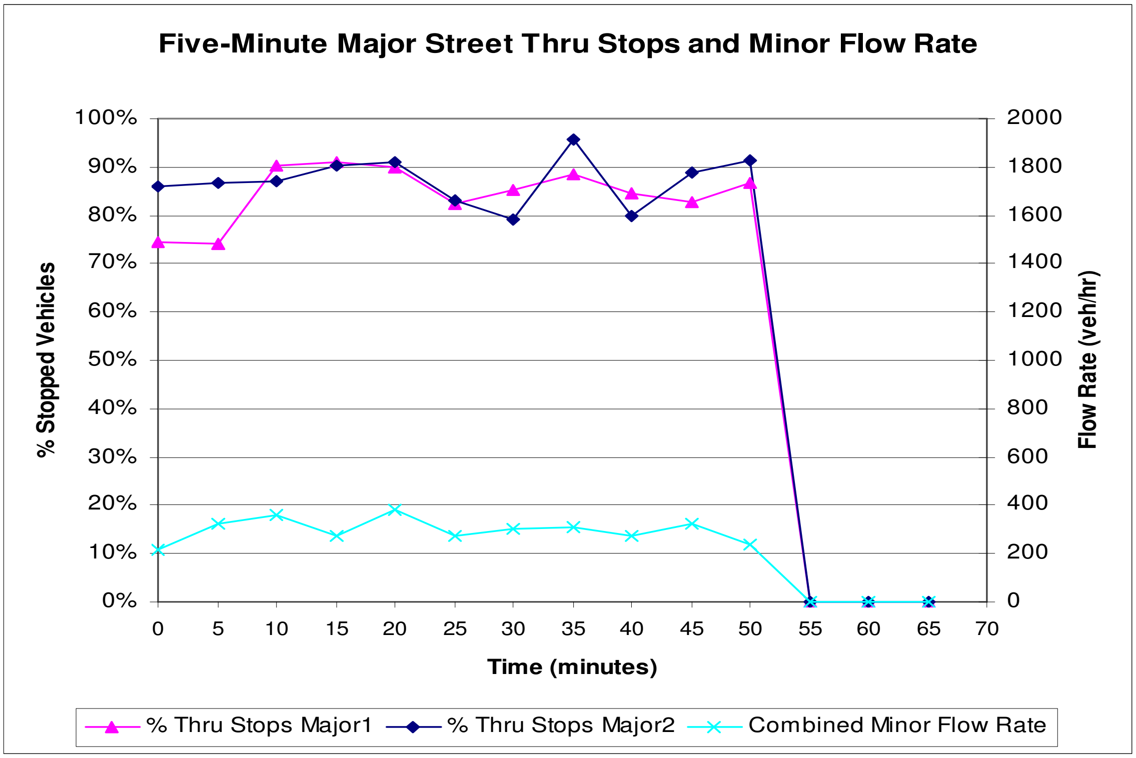


Figure D.1 Five-Minute Major Street Vehicle Stops at Piedmont Rd./The Prado

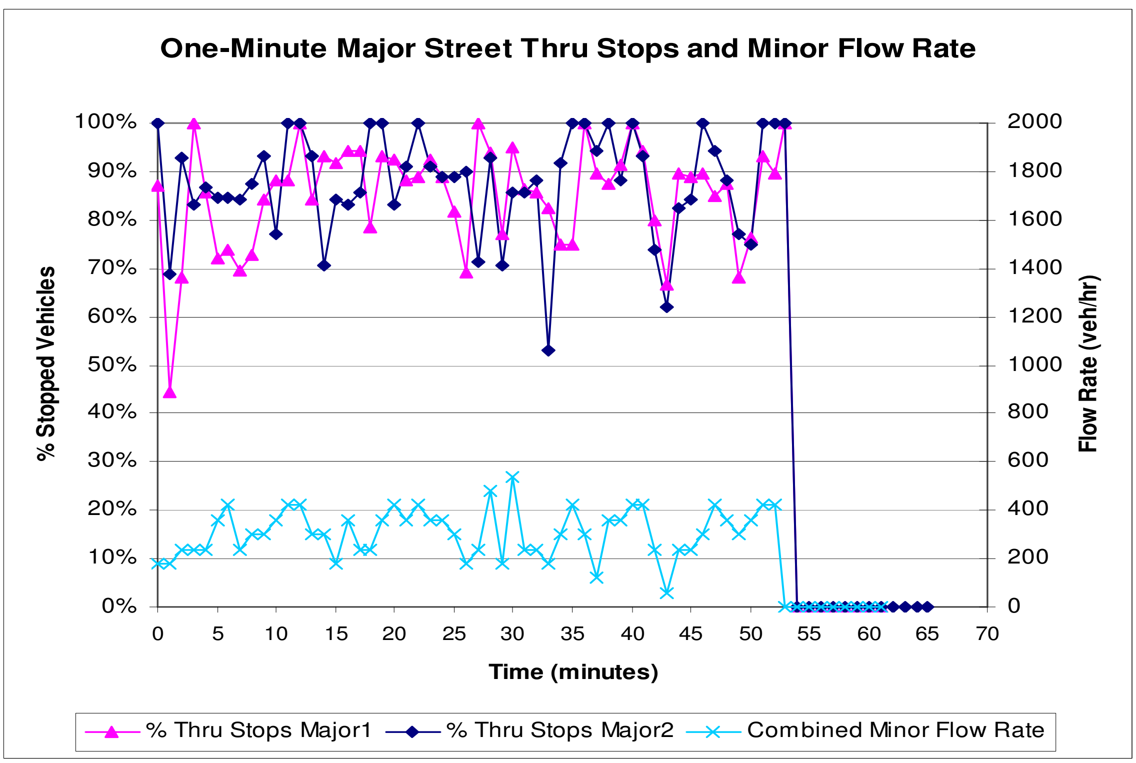


Figure D.2 One-Minute Major Street Vehicle Stops at Piedmont Rd./The Prado

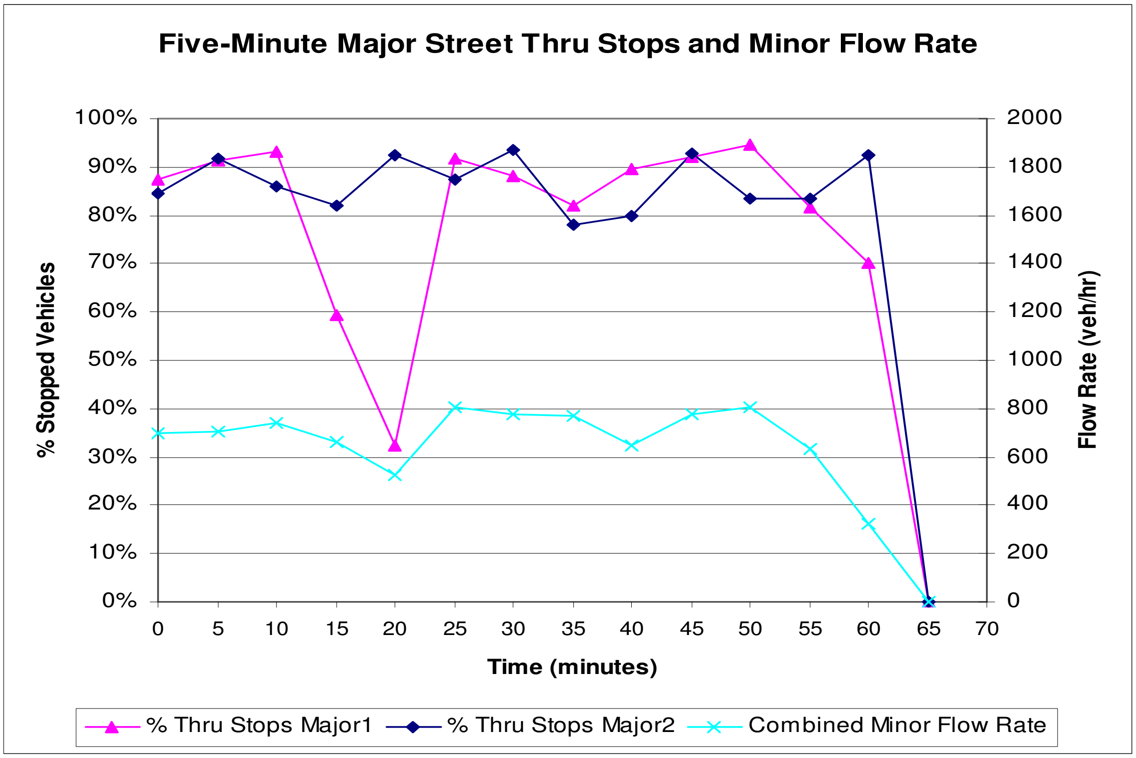


Figure D.3 Five-Minute Major Street Vehicle Stops at Roswell Rd./W. Wieuca Rd.

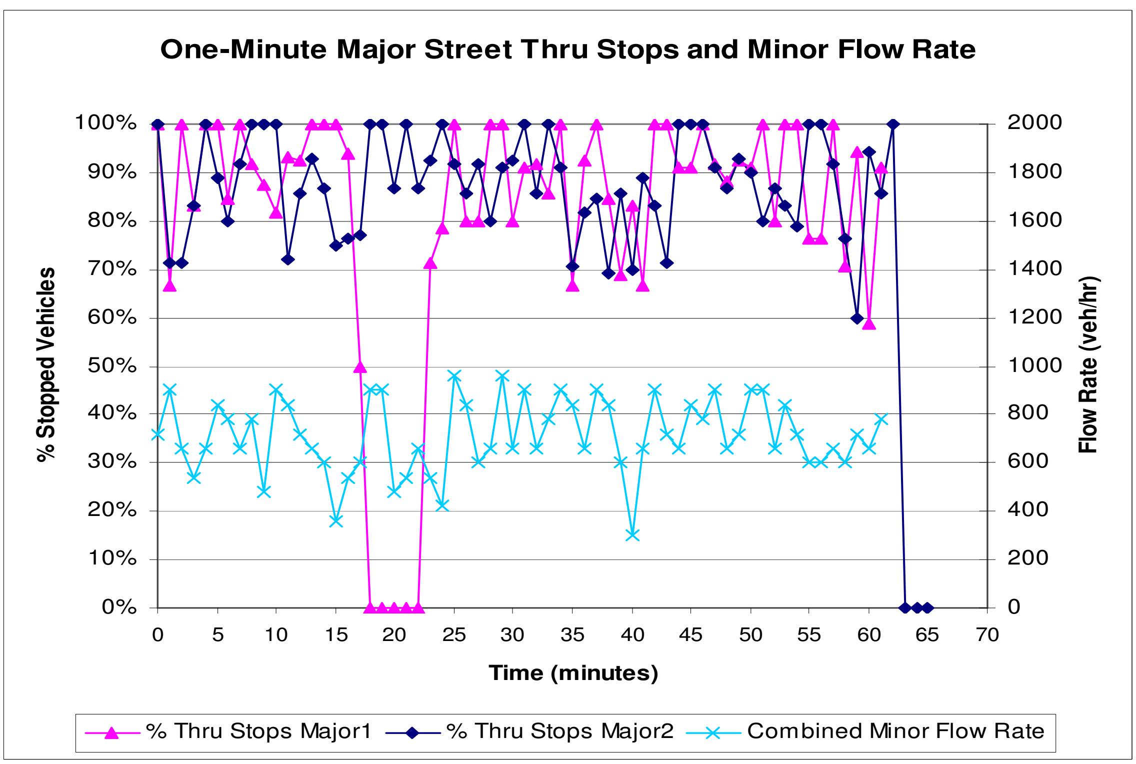


Figure D.4 One-Minute Major Street Vehicle Stops at Roswell Rd./W. Wieuca Rd.

APPENDIX E

ONE- AND FIVE-MINUTE MAJOR STREET PLATOON STOPS AT

YELLOW/RED FLASHING SIGNALS

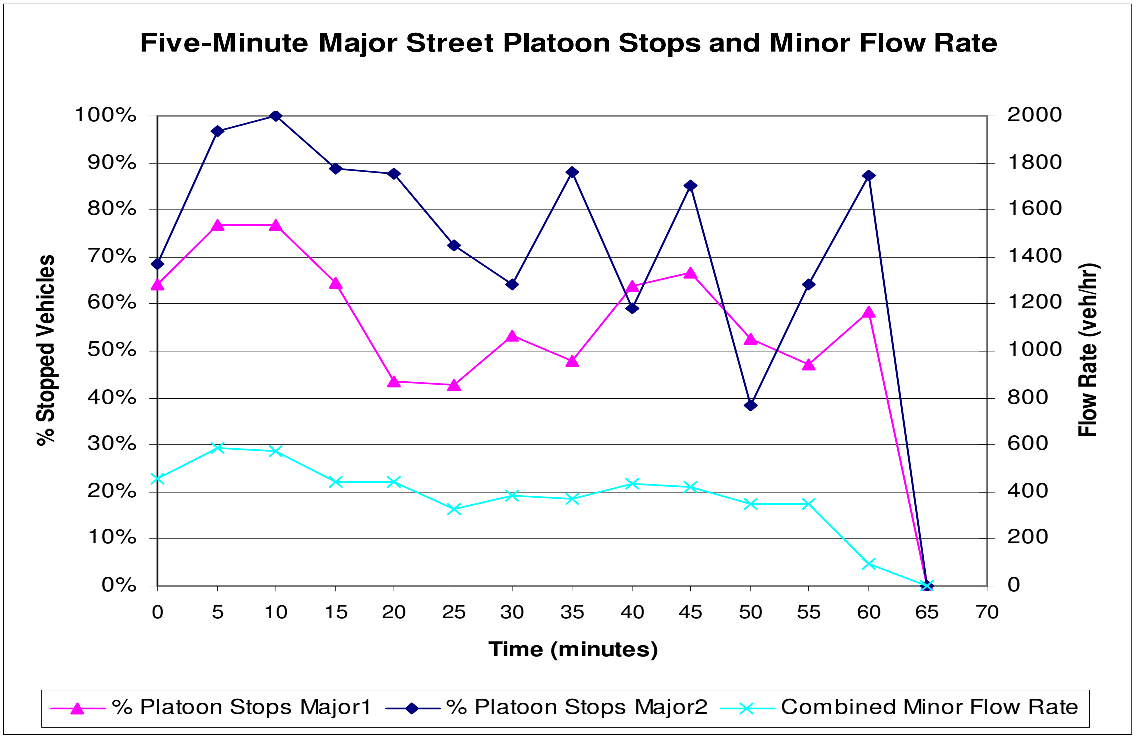


Figure E.1 Five-Minute Major Street Platoon Stops at Northside Dr./Peachtree Battle Ave.

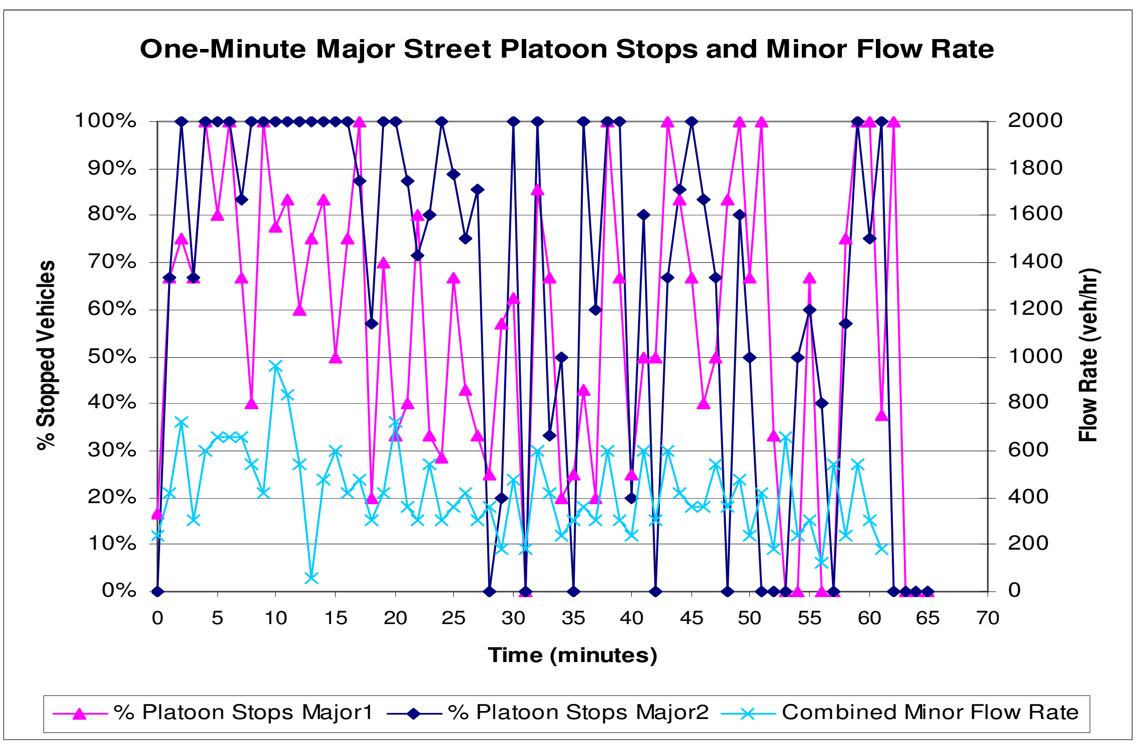


Figure E.2 One-Minute Major Street Platoon Stops at Northside Dr./Peachtree Battle Ave.

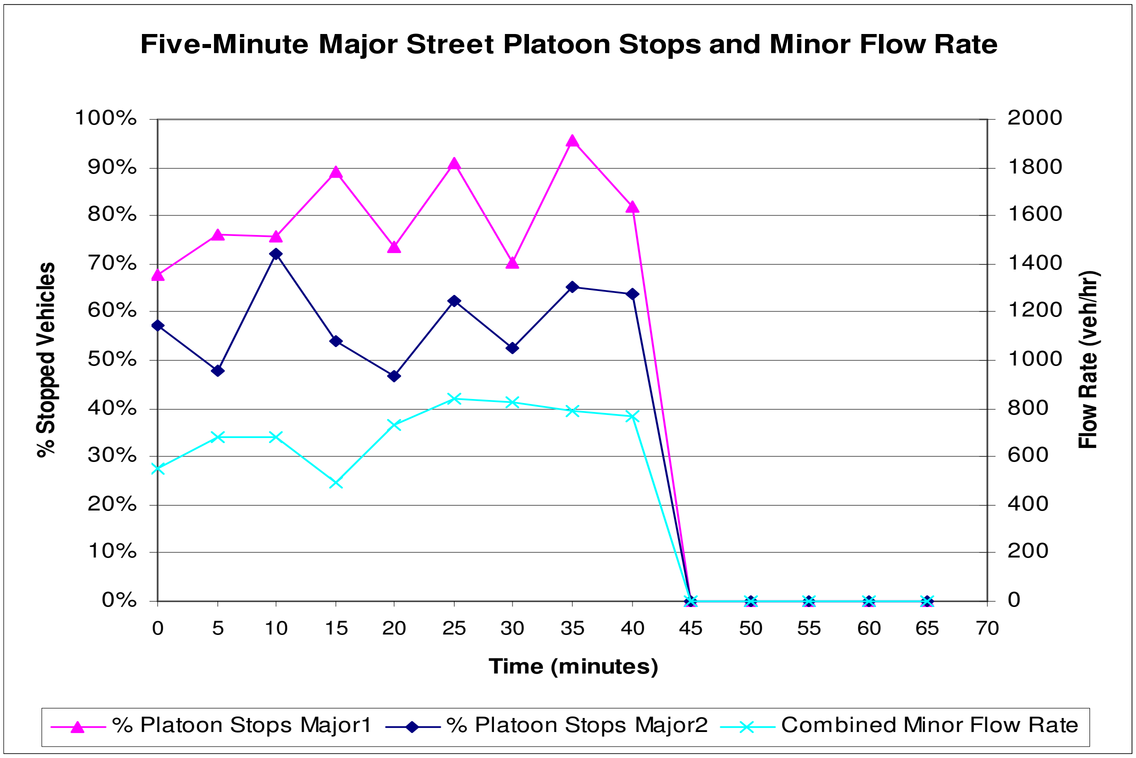


Figure E.3 Five-Minute Major Street Platoon Stops at Monroe Dr./10th St.

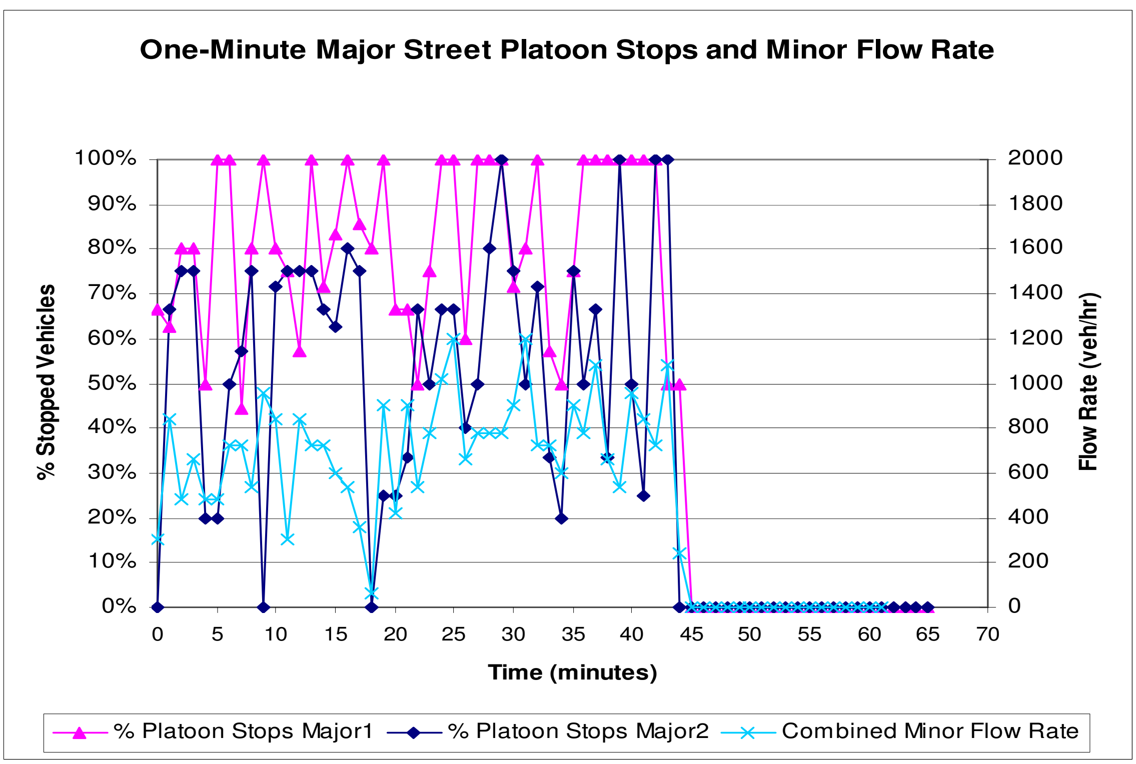


Figure E.4 One-Minute Major Street Platoon Stops at Monroe Dr./10th St.

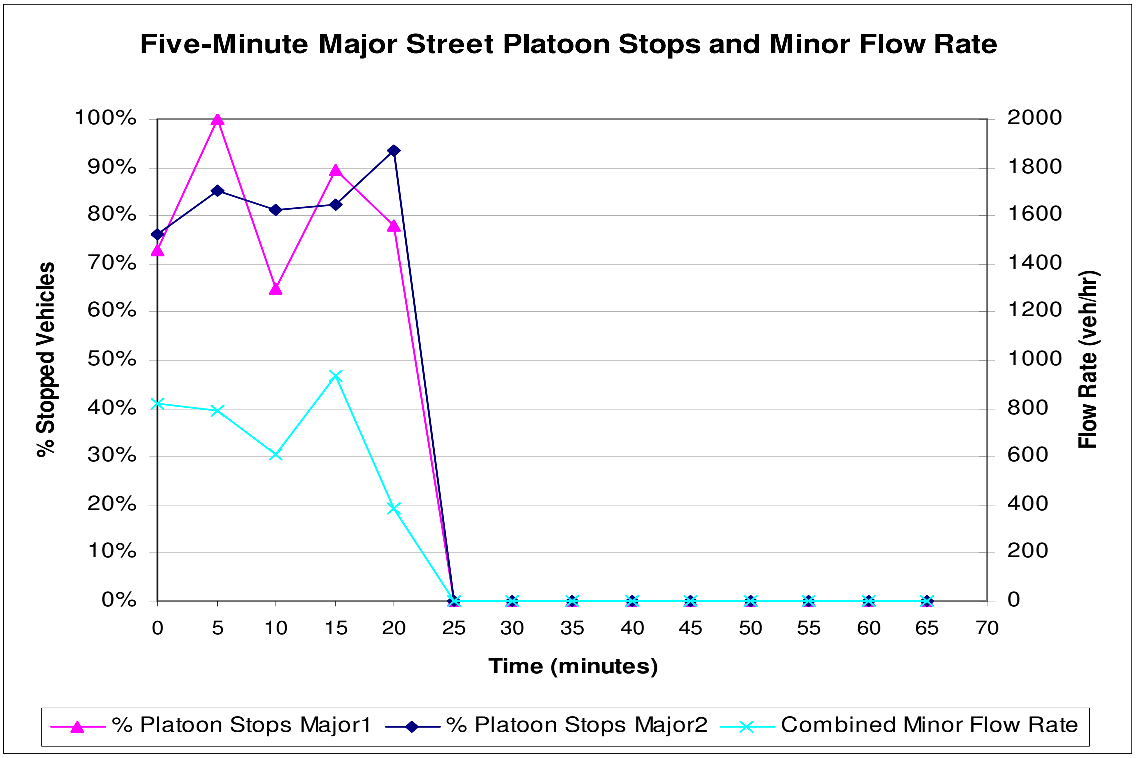


Figure E.5 Five-Minute Major Street Platoon Stops at Rainbow St./Candler Dr.

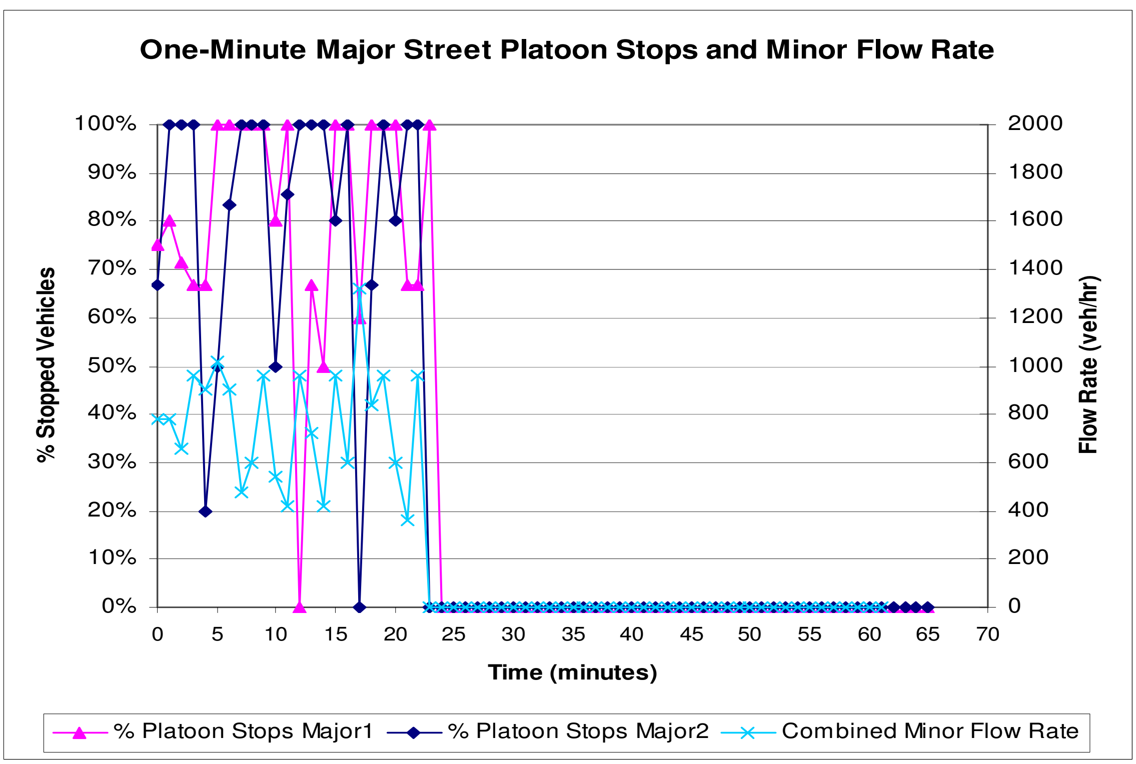


Figure E.6 One-Minute Major Street Platoon Stops at Rainbow St./Candler Dr.

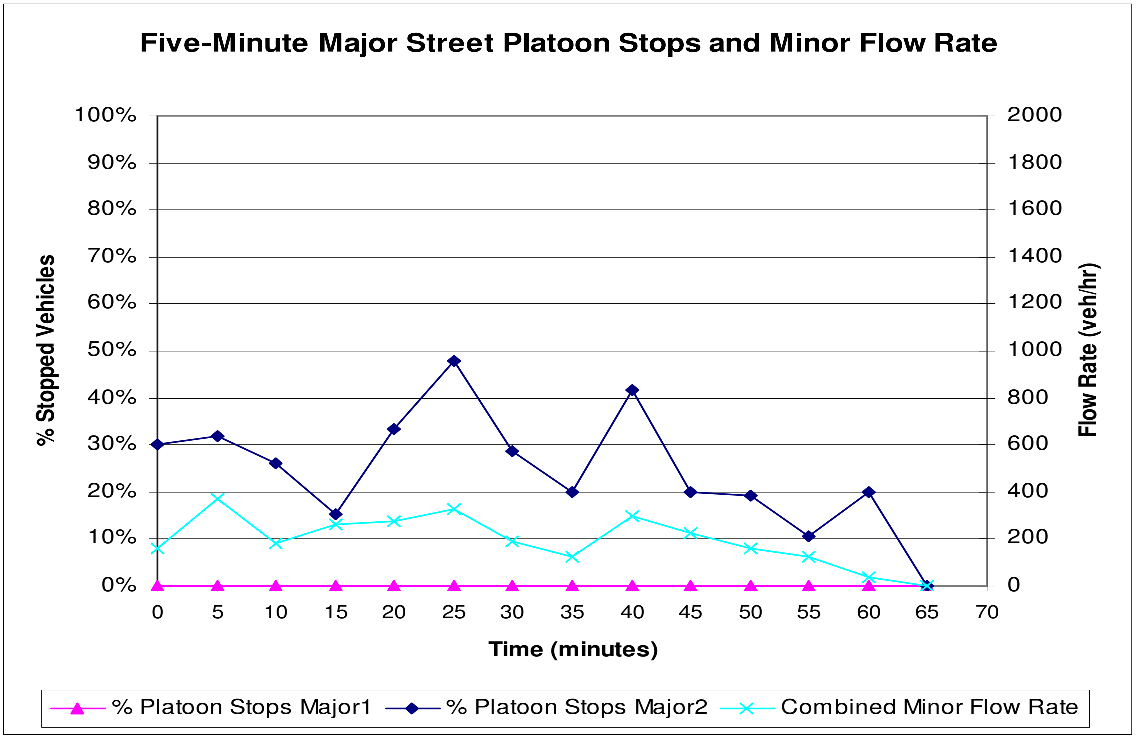


Figure E.7 Five-Minute Major Street Platoon Stops at N. Highland Ave./University Dr.

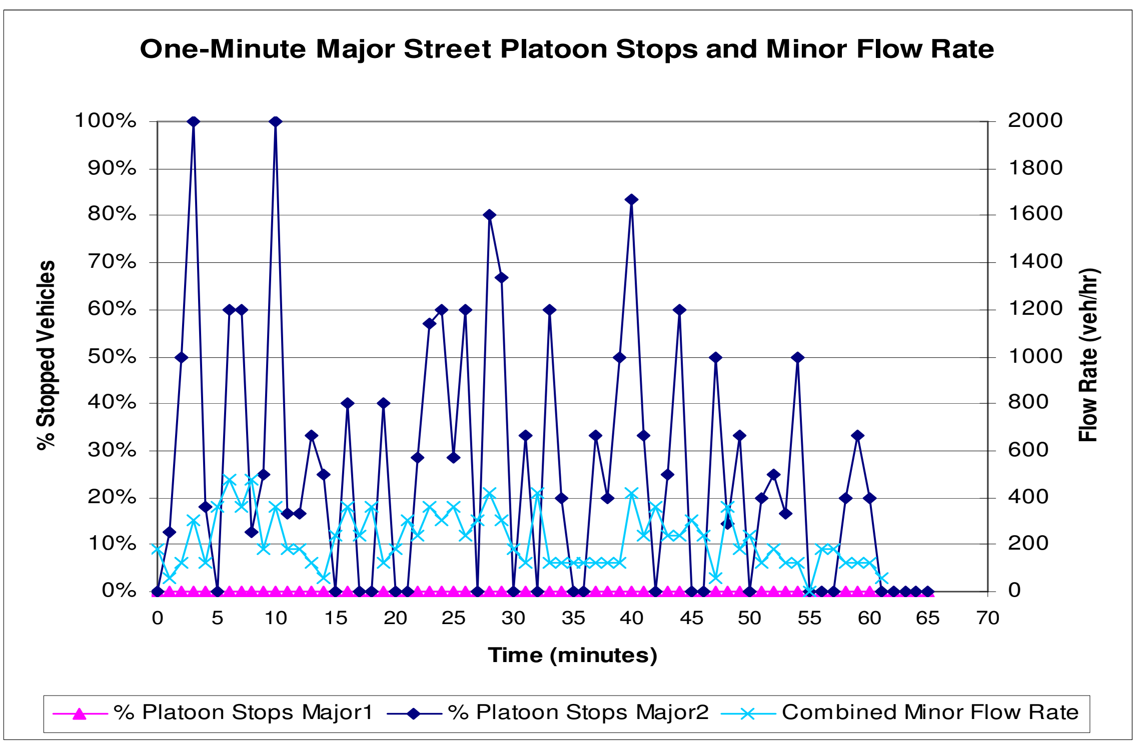


Figure E.8 One-Minute Major Street Platoon Stops at N. Highland Ave./University Dr.

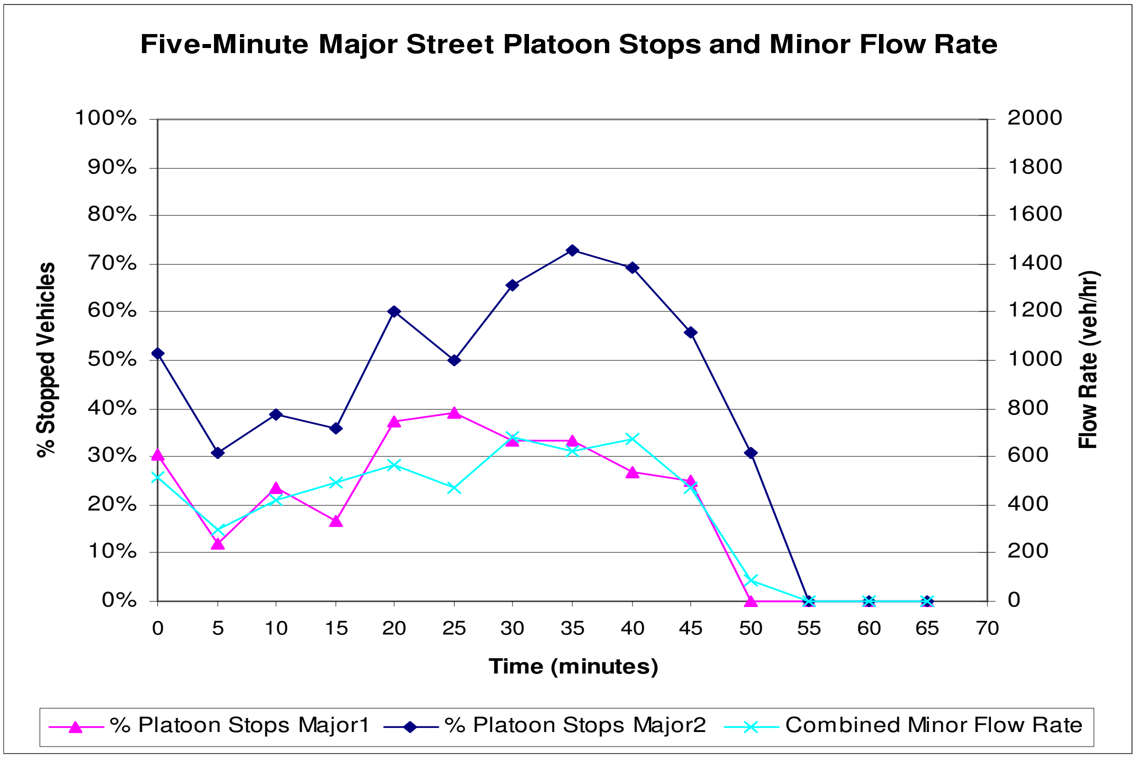


Figure E.9 Five-Minute Major Street Platoon Stops at Lenox Rd./Phipps Blvd.

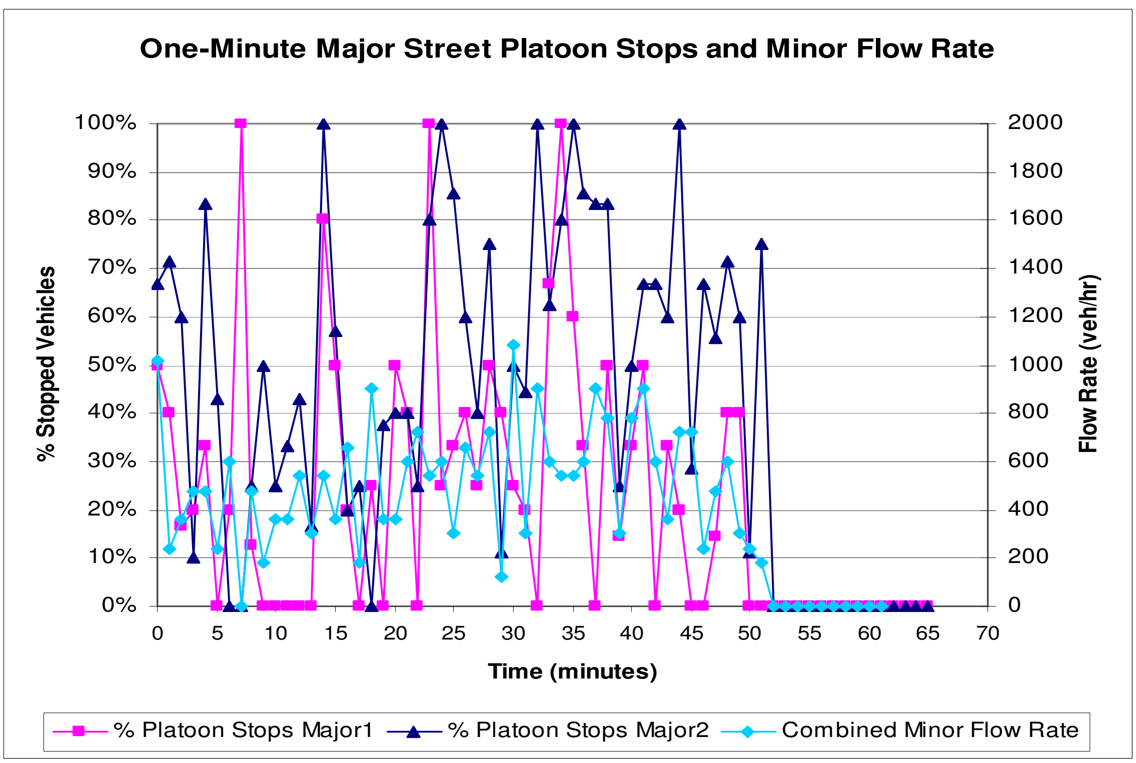


Figure E.10 One-Minute Major Street Platoon Stops at Lenox Rd./Phipps Blvd.

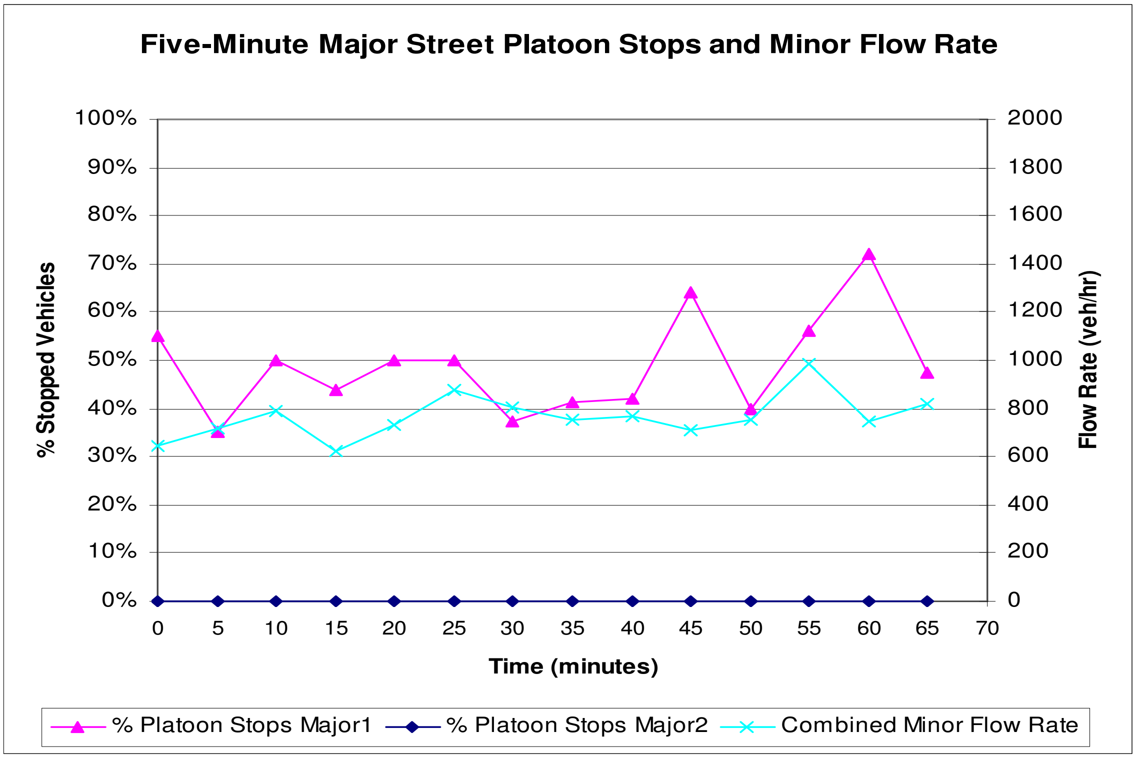


Figure E.11 Five-Minute Major Street Platoon Stops at Spring St./17th St.

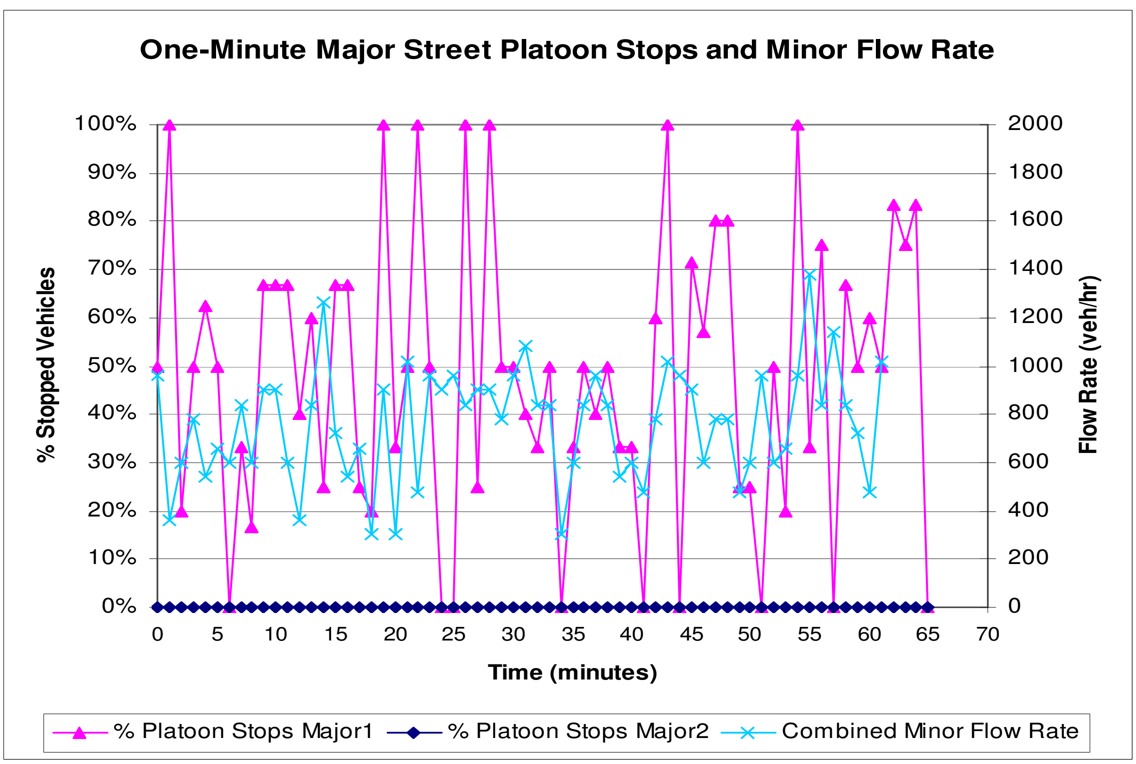


Figure E.12 One-Minute Major Street Platoon Stops at Spring St./17th St.

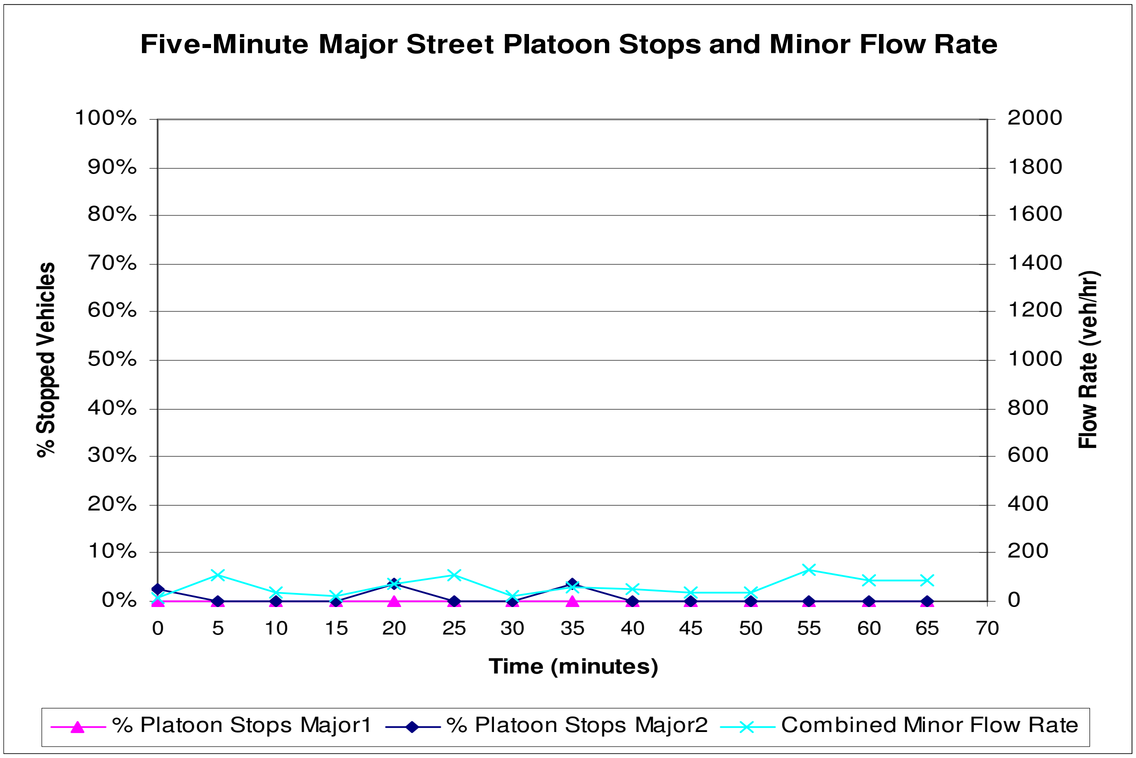


Figure E.13 Five-Minute Major Street Platoon Stops at W. Peachtree St./11th St.

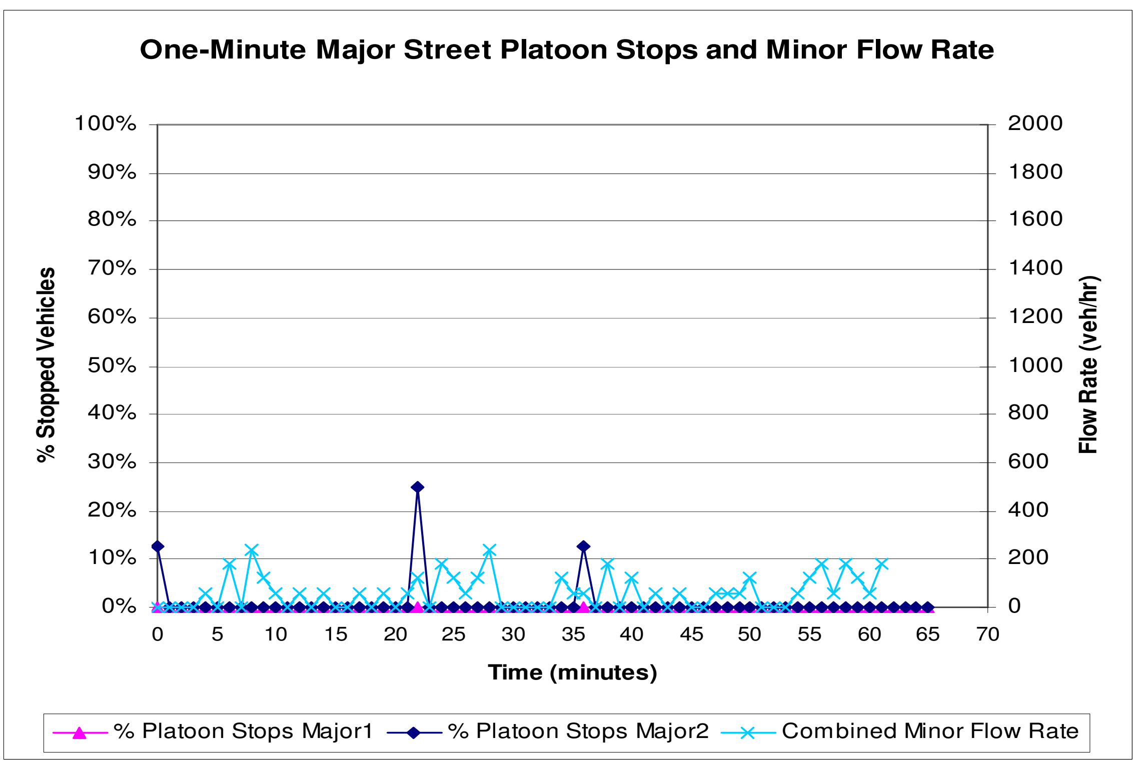


Figure E.14 One-Minute Major Street Platoon Stops at W. Peachtree St./11th St.

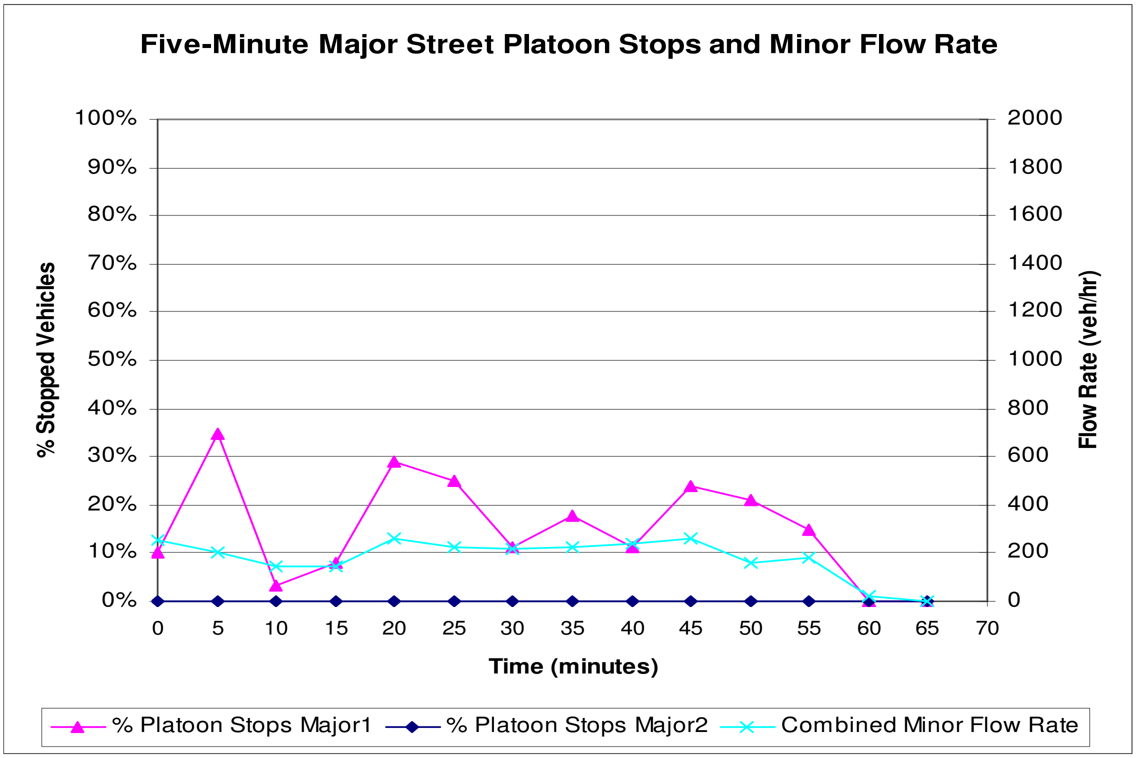


Figure E.15 Five-Minute Major Street Platoon Stops at W. Peachtree St./16th St.

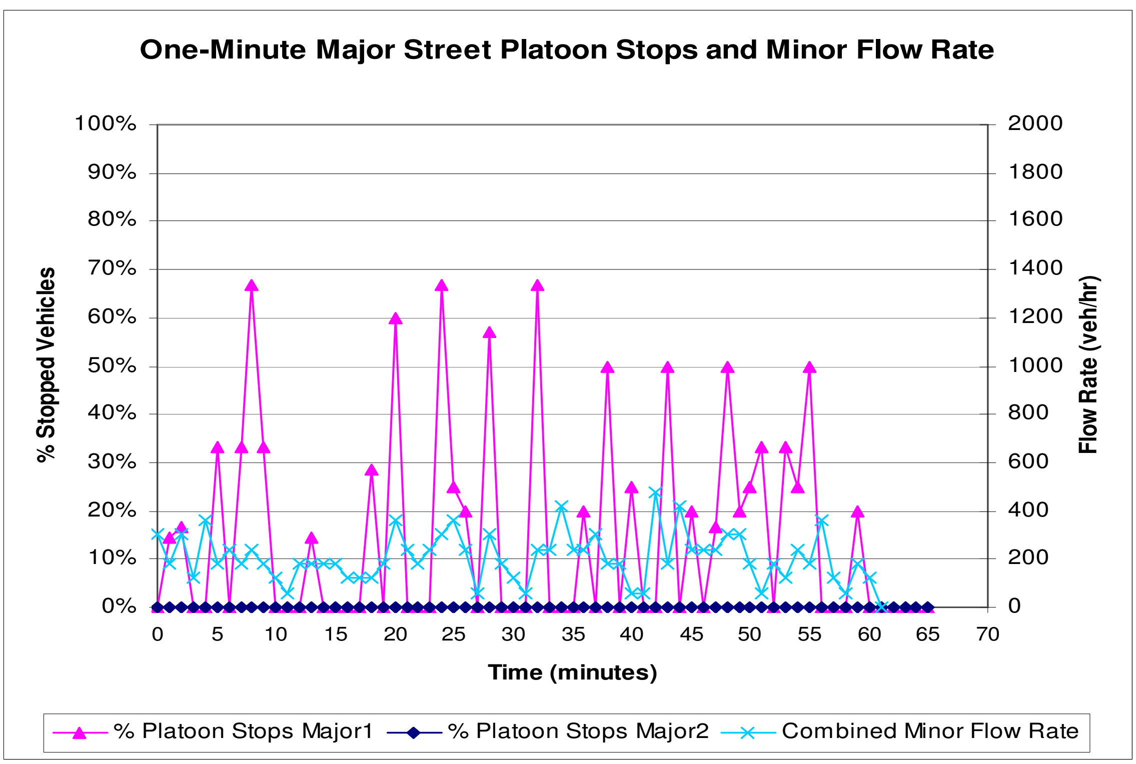


Figure E.16 One-Minute Major Street Platoon Stops at W. Peachtree St./16th St.

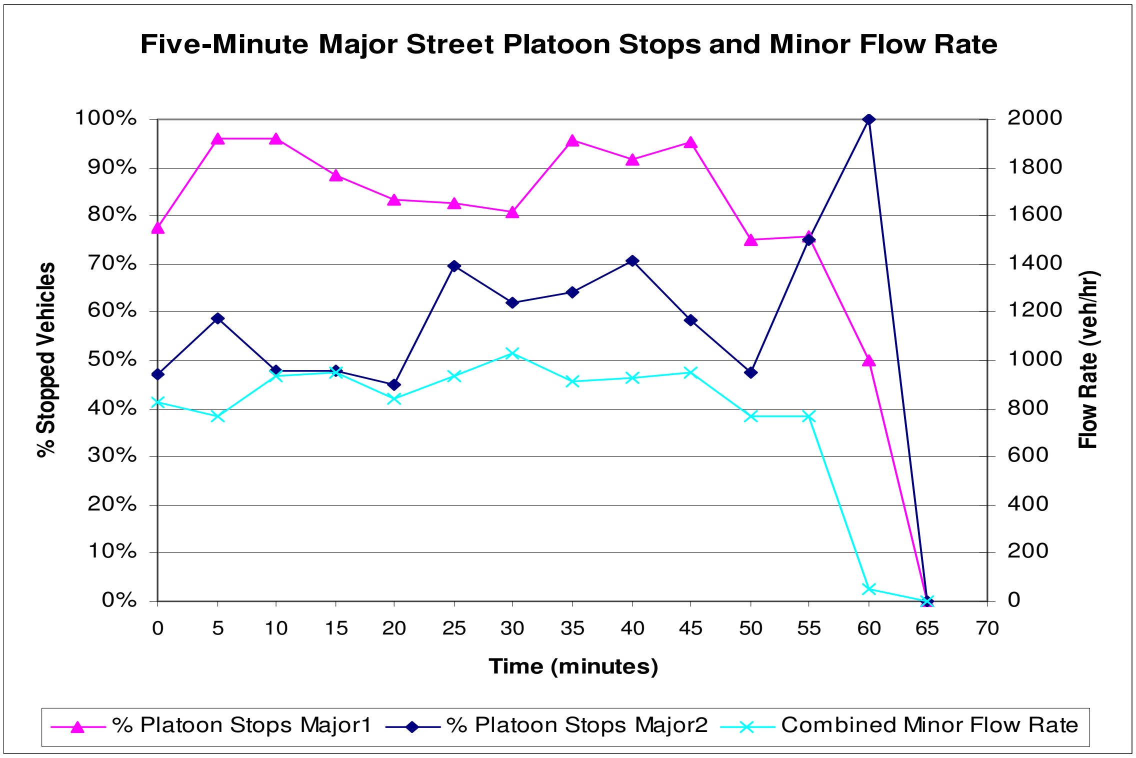


Figure E.17 Five-Minute Major Street Platoon Stops at 14th St./William St.

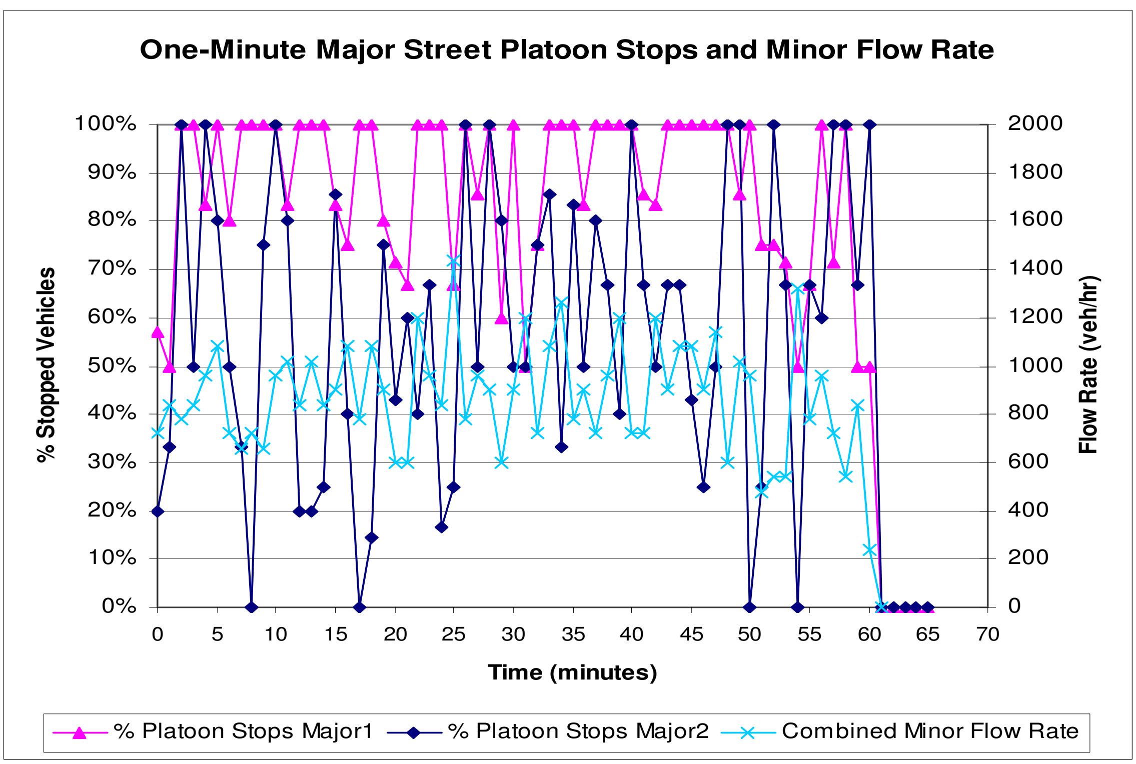


Figure E.18 One-Minute Major Street Platoon Stops at 14th St./William St.

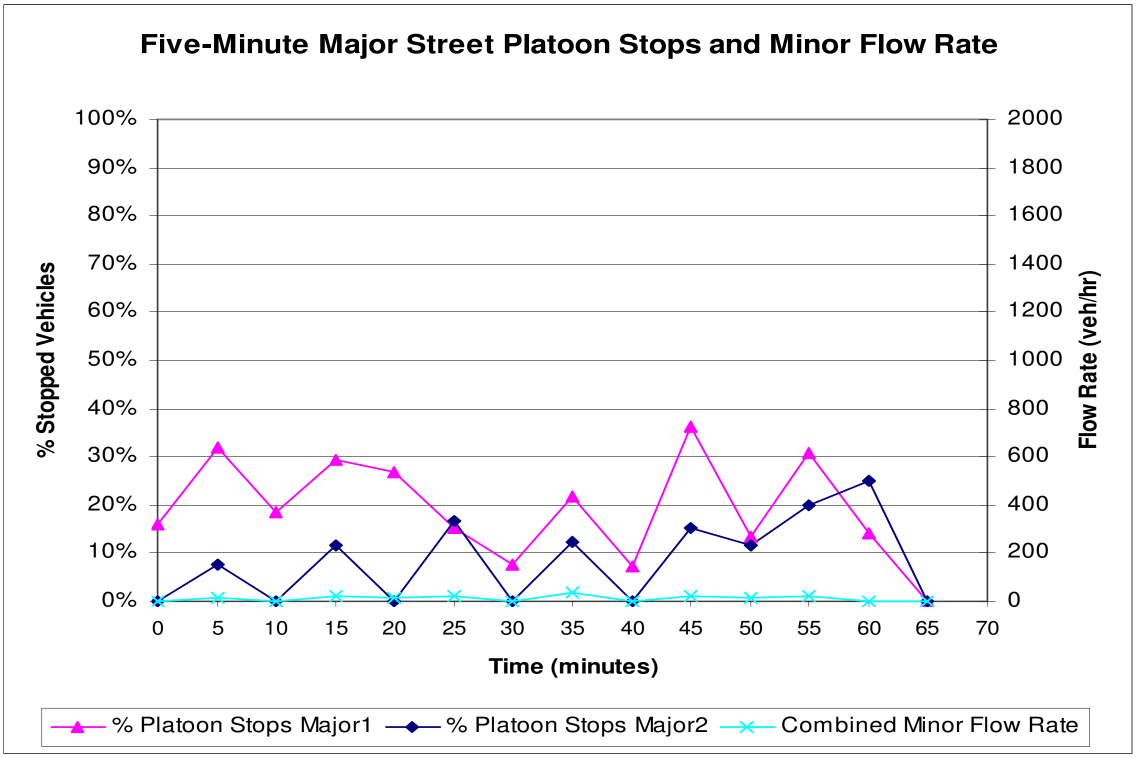


Figure E.19 Five-Minute Major Street Platoon Stops at Market St./16th St.

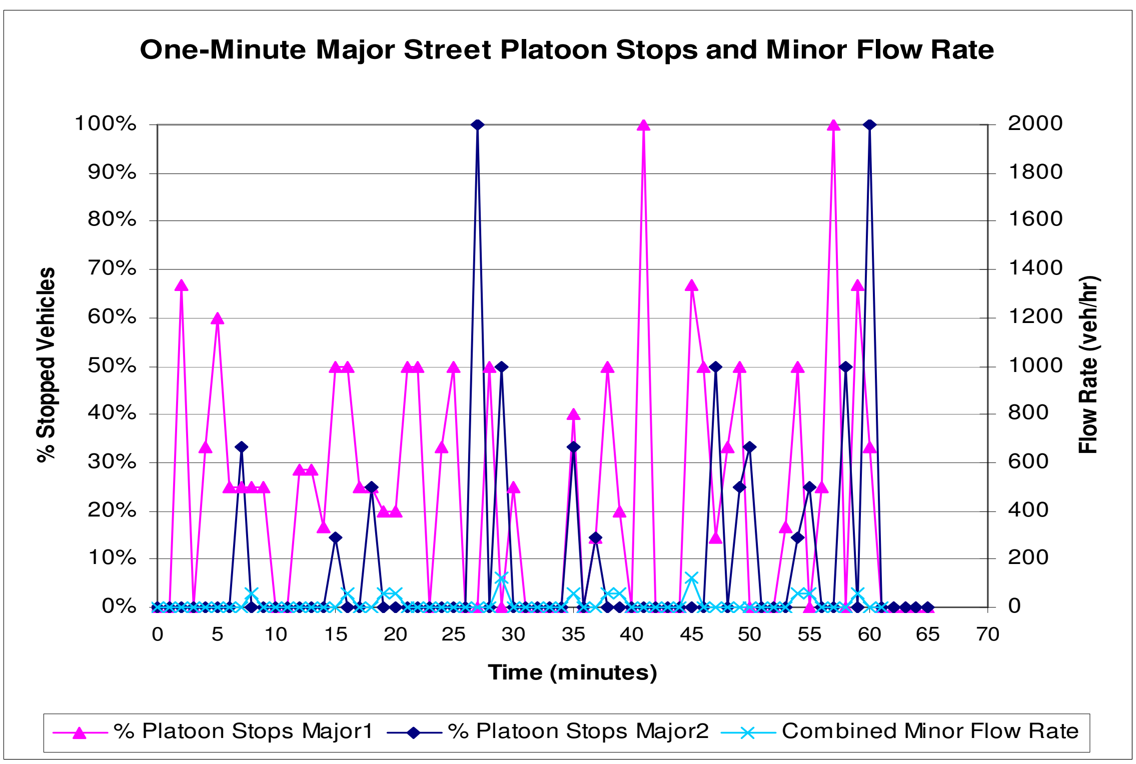


Figure E.20 One-Minute Major Street Platoon Stops at Market St./16th St.

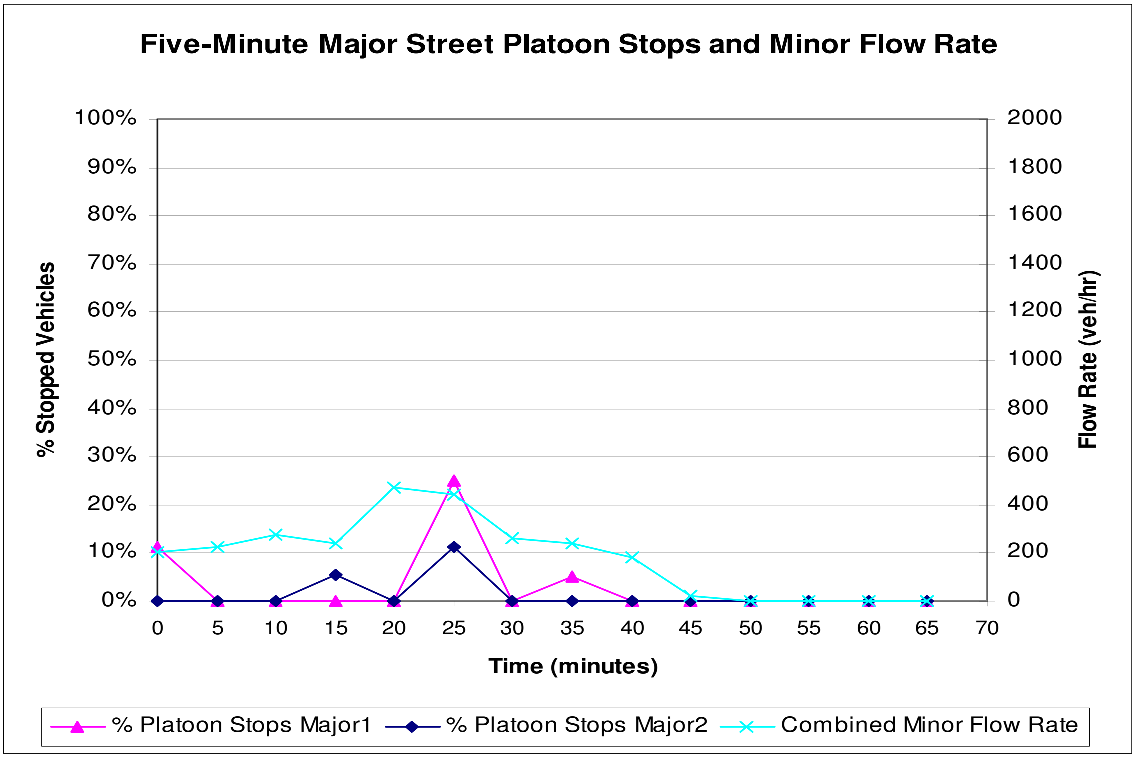


Figure E.21 Five-Minute Major Street Platoon Stops at 17th St./Bishop St.

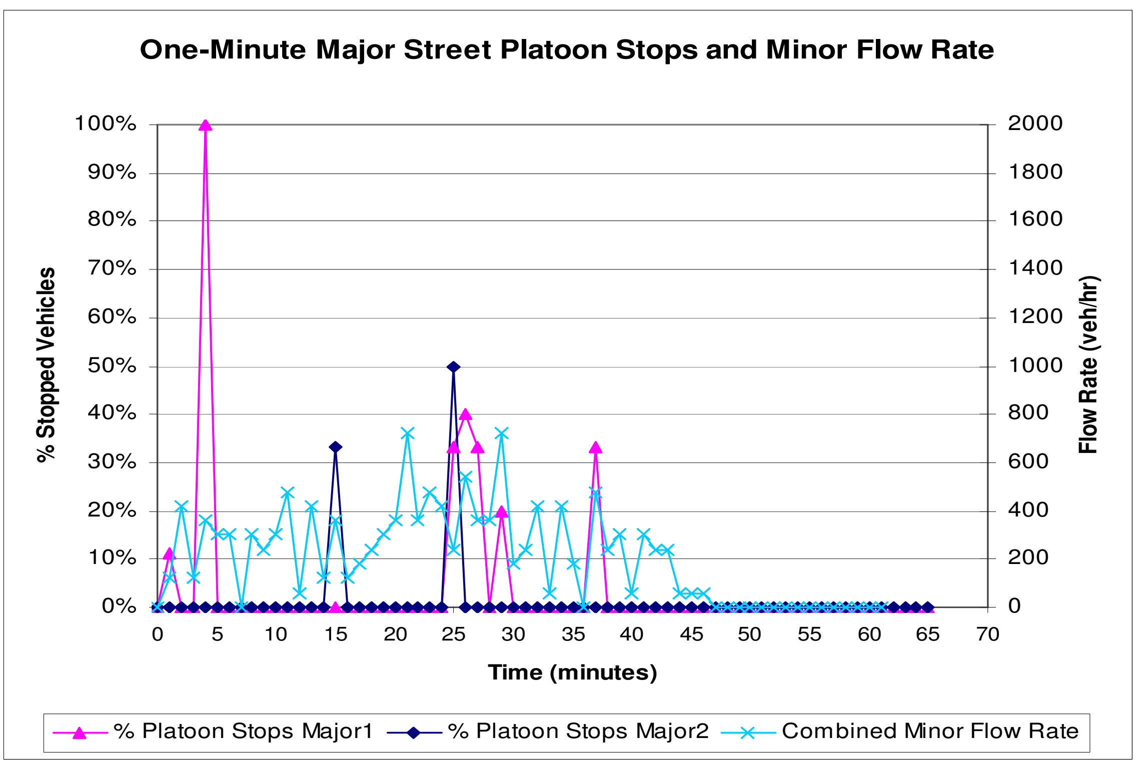


Figure E.22 One-Minute Major Street Platoon Stops at 17th St./Bishop St.

APPENDIX F

ONE- AND FIVE-MINUTE MAJOR STREET PLATOON STOPS AT RED/RED FLASHING SIGNALS

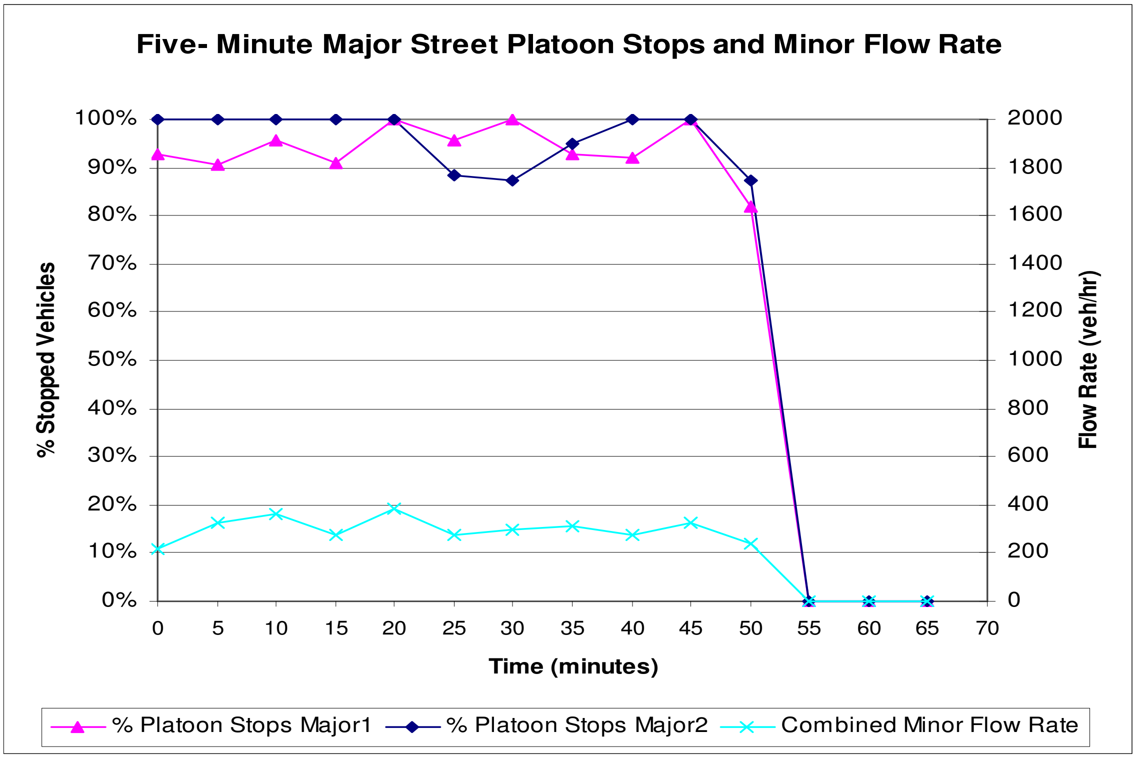


Figure F.1 Five-Minute Major Street Platoon Stops at Piedmont Rd./The Prado

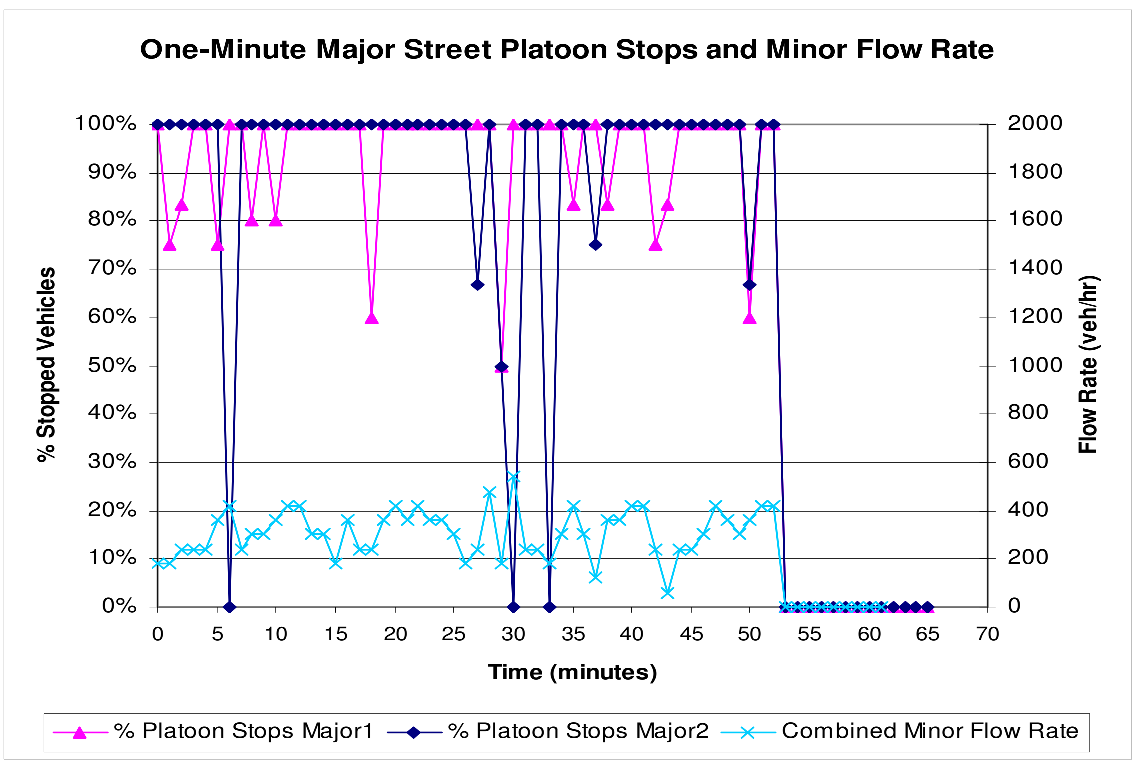


Figure F.2 One-Minute Major Street Platoon Stops at Piedmont Rd./The Prado

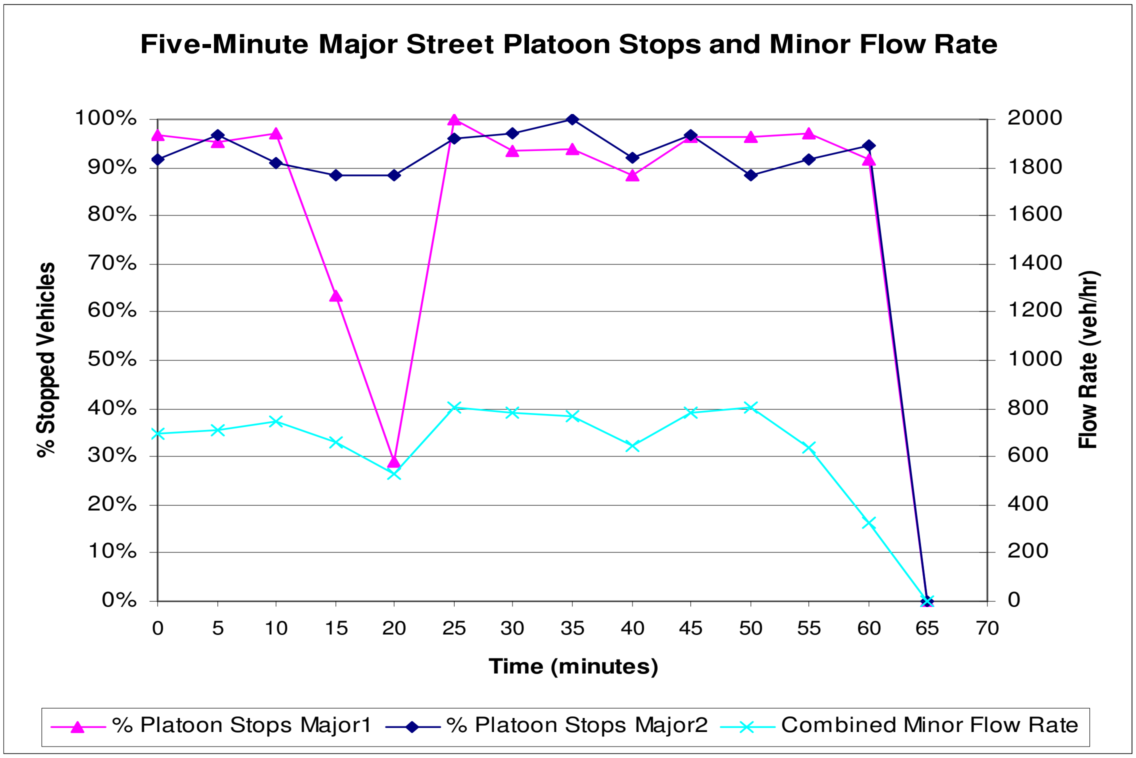


Figure F.3 Five-Minute Major Street Platoon Stops at Roswell Rd./W. Wieuca Rd.

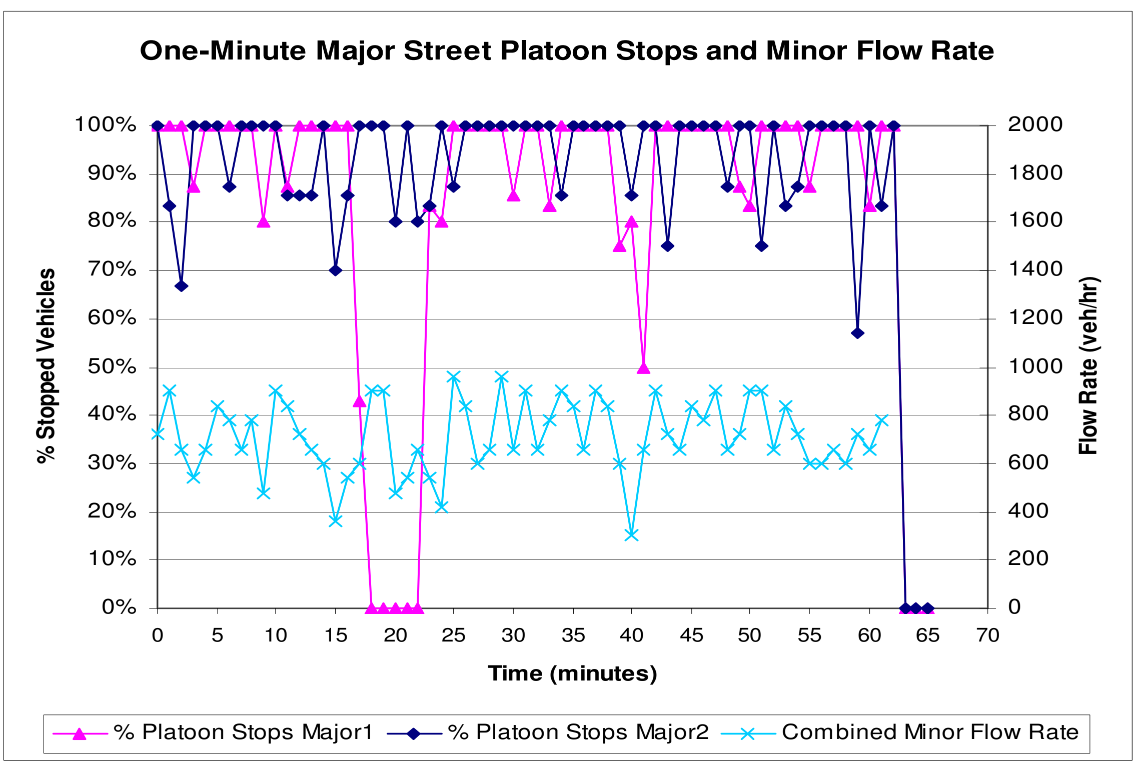
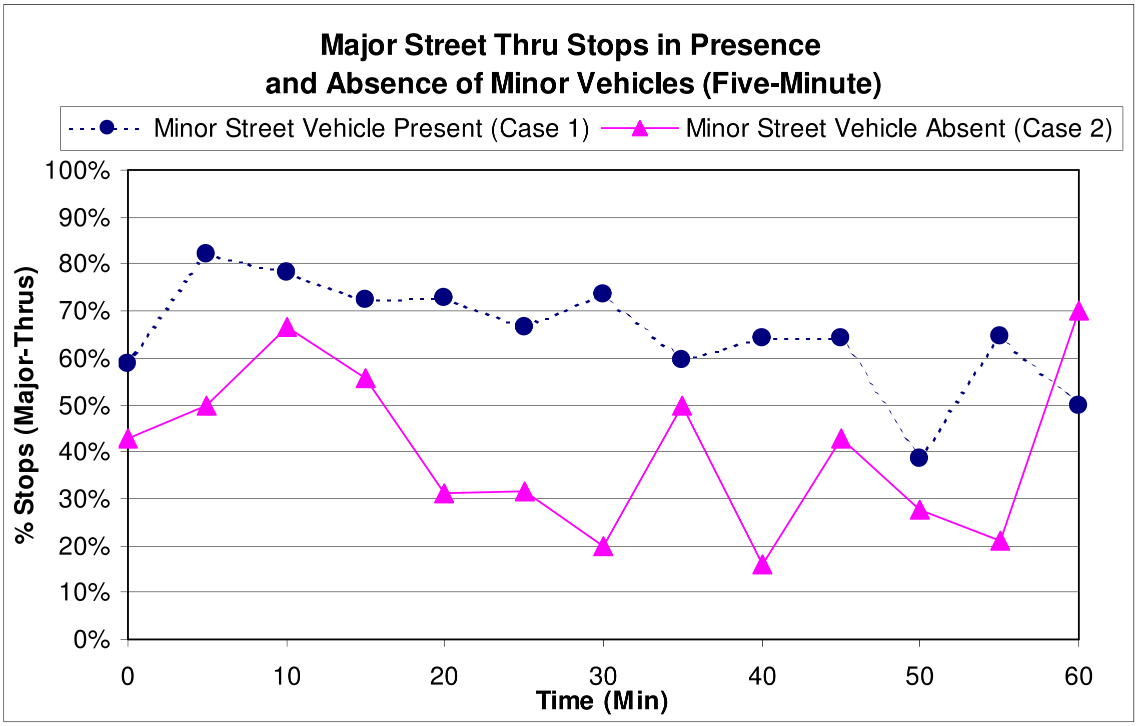


Figure F.4 One-Minute Major Street Platoon Stops at Roswell Rd./W. Wieuca Rd.

APPENDIX G

ONE- AND FIVE-MINUTE MAJOR STREET THRU STOPS IN THE PRESENCE AND ABSENCE OF MINOR STREET VEHICLES AT YELLOW/RED FLASHING SIGNALS



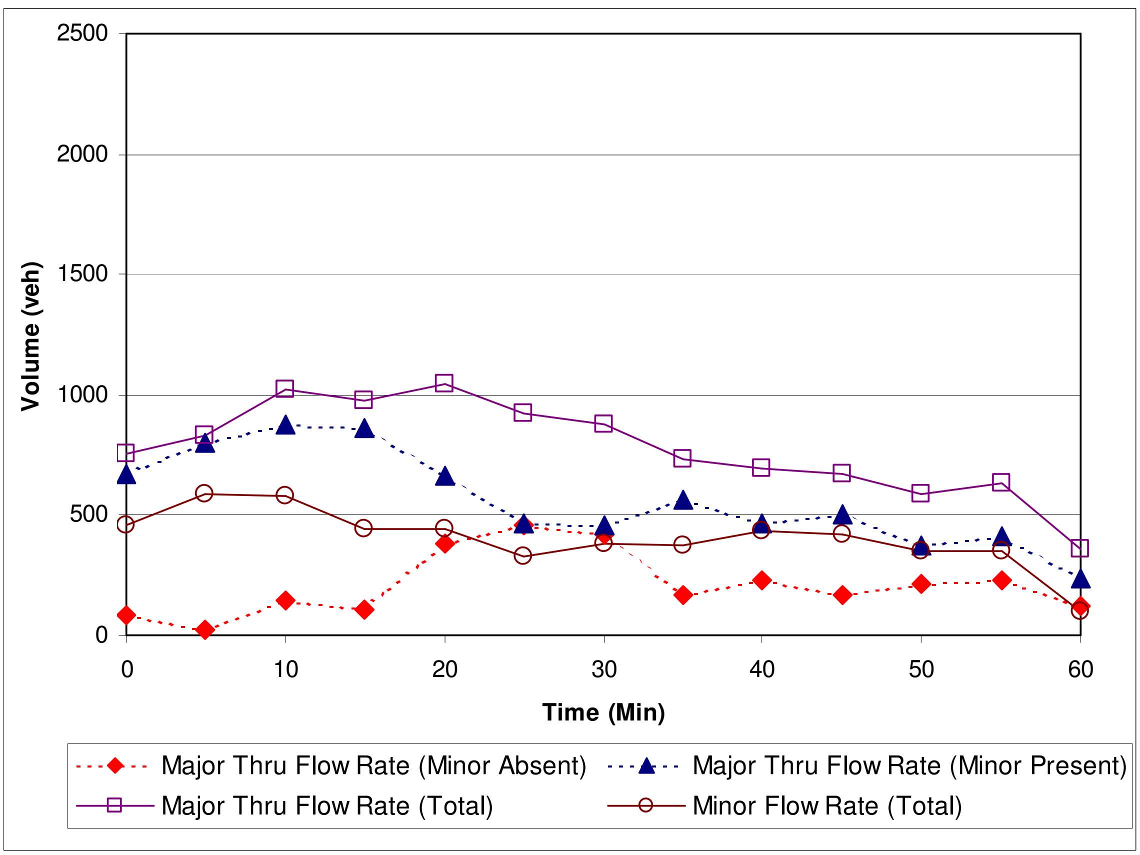
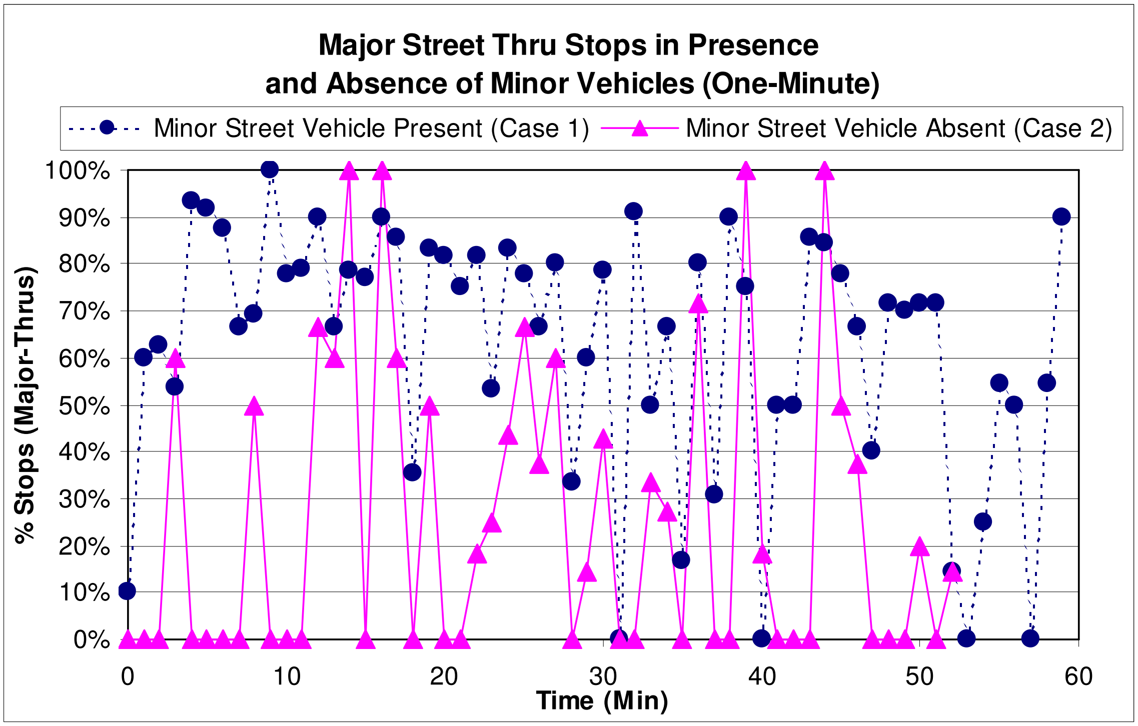


Figure G.1 Five-Minute Presence and Absence Analysis at Northside Dr./Peachtree Battle Ave.



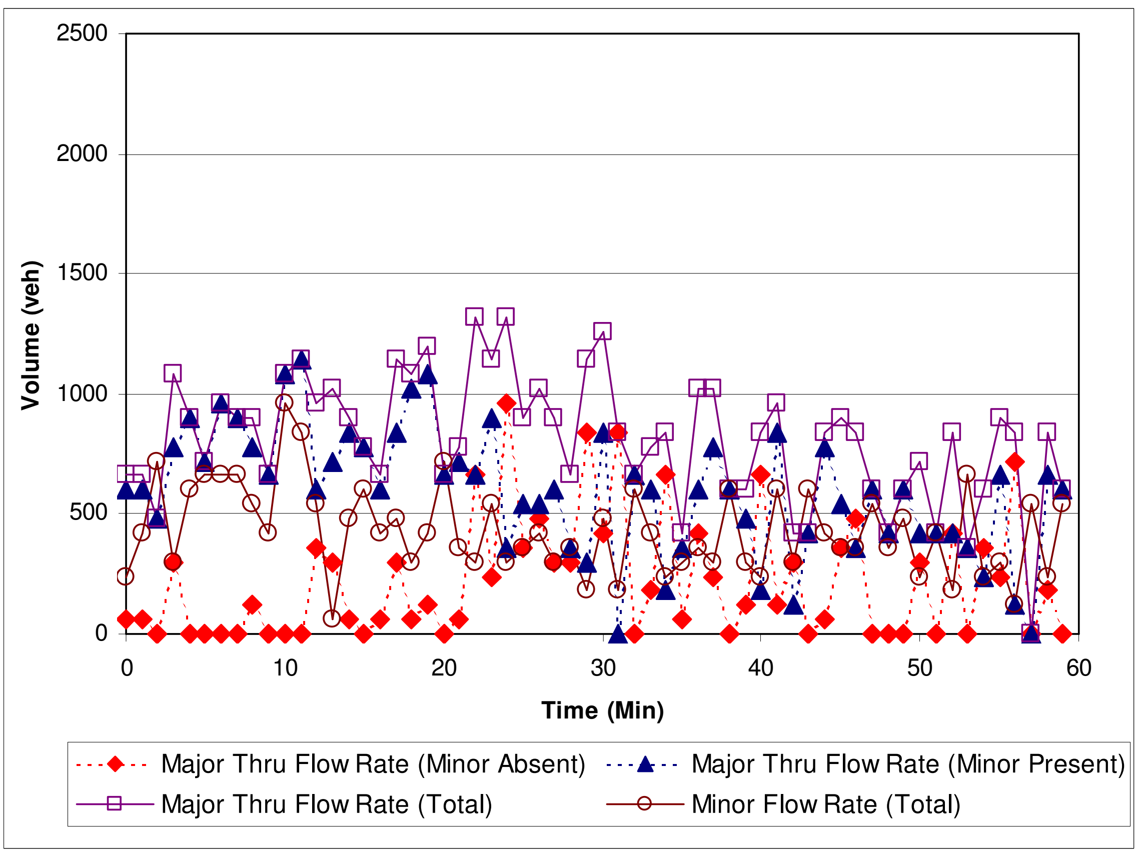
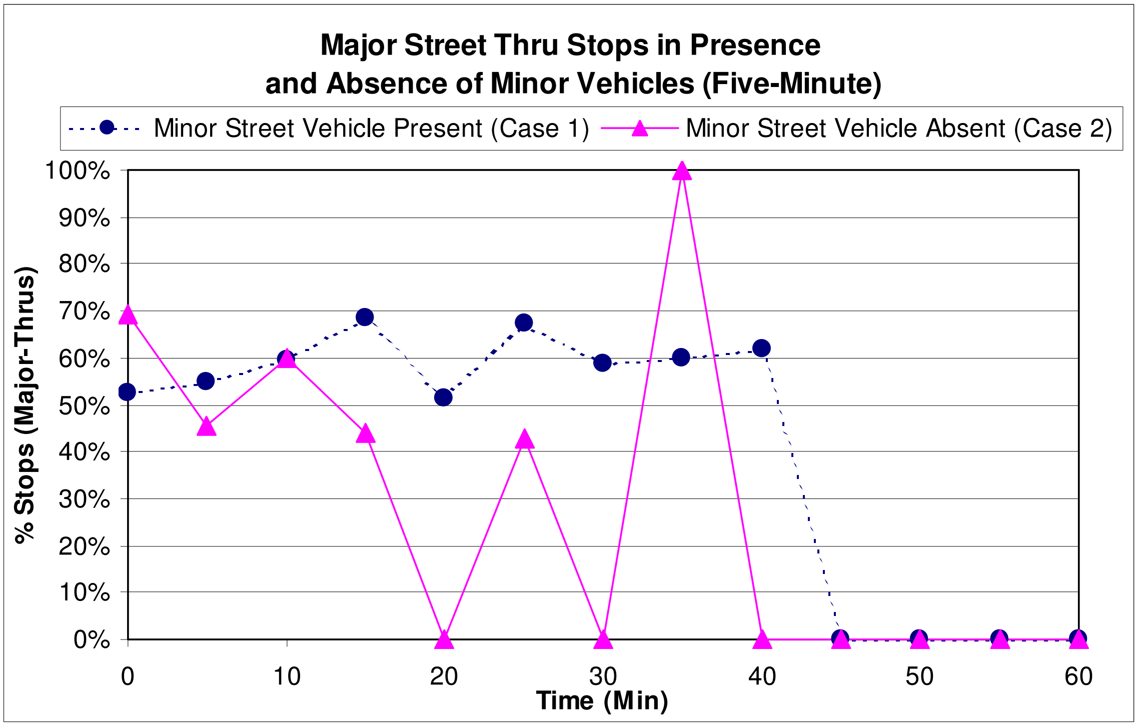


Figure G.2 One-Minute Presence and Absence Analysis at Northside Dr./Peachtree Battle Ave.



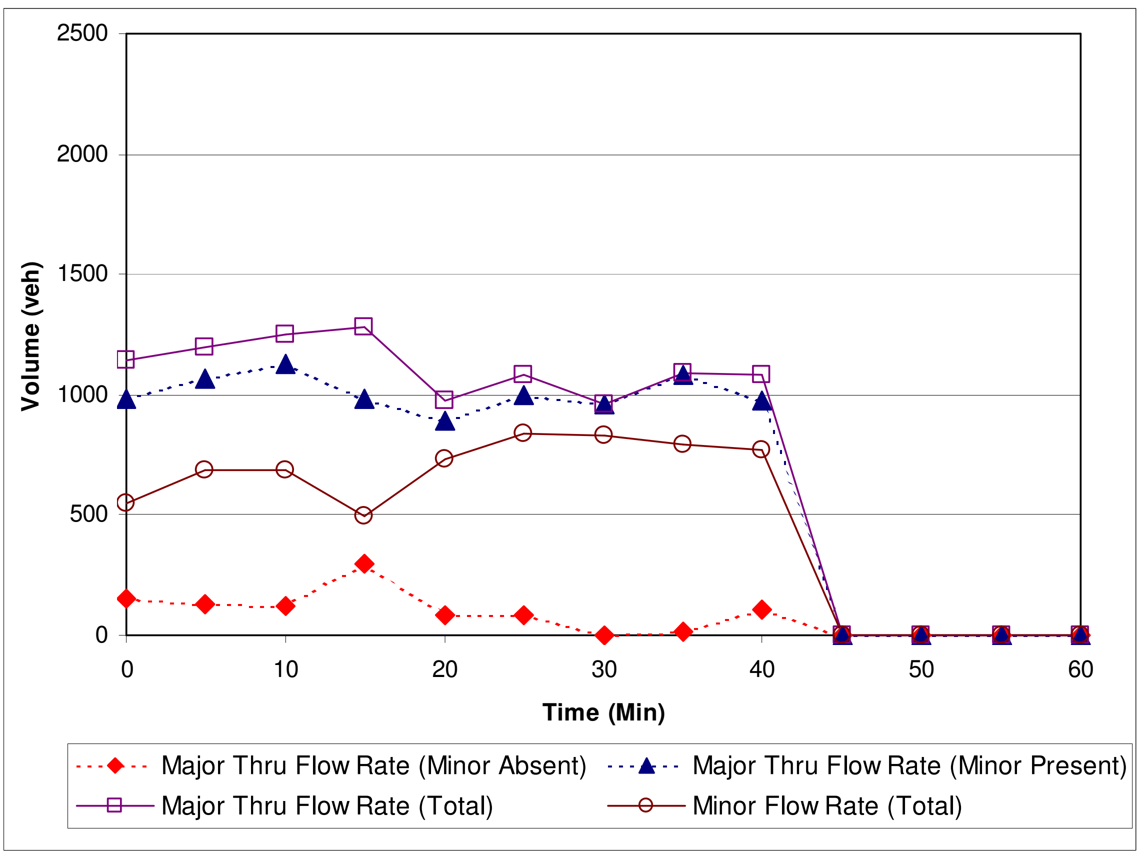
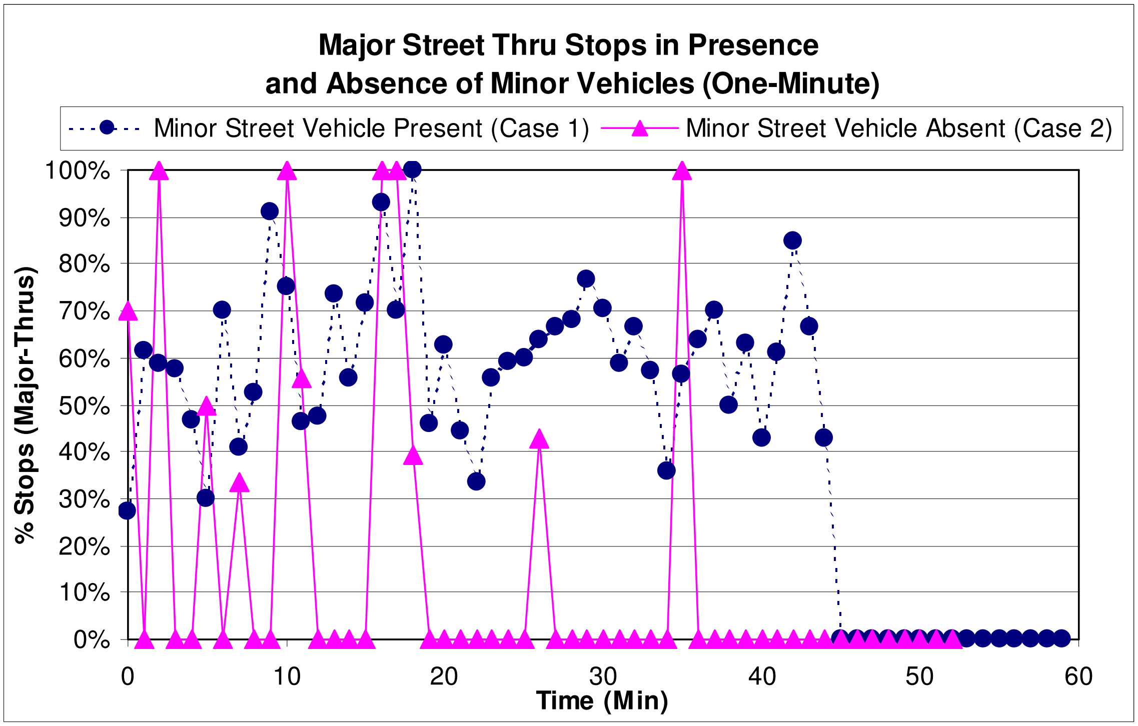


Figure G.3 Five-Minute Presence and Absence Analysis at Monroe Dr./10th St.



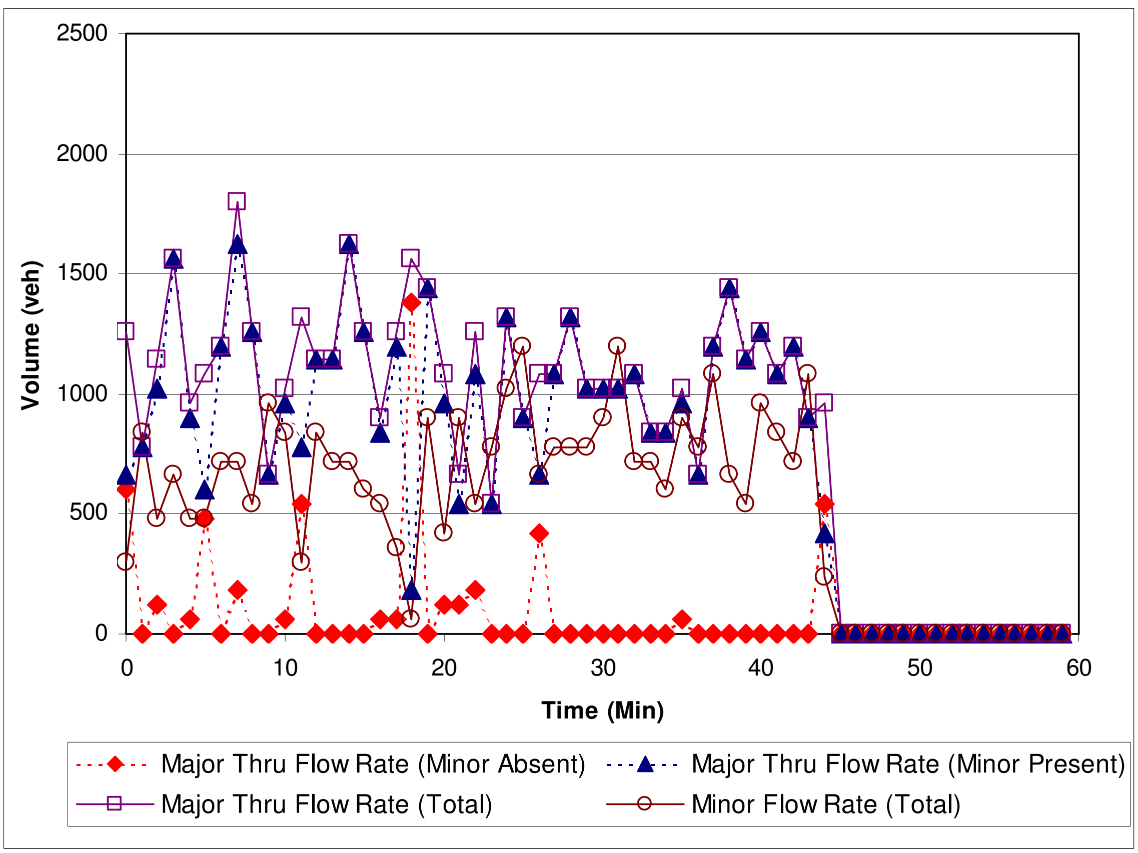
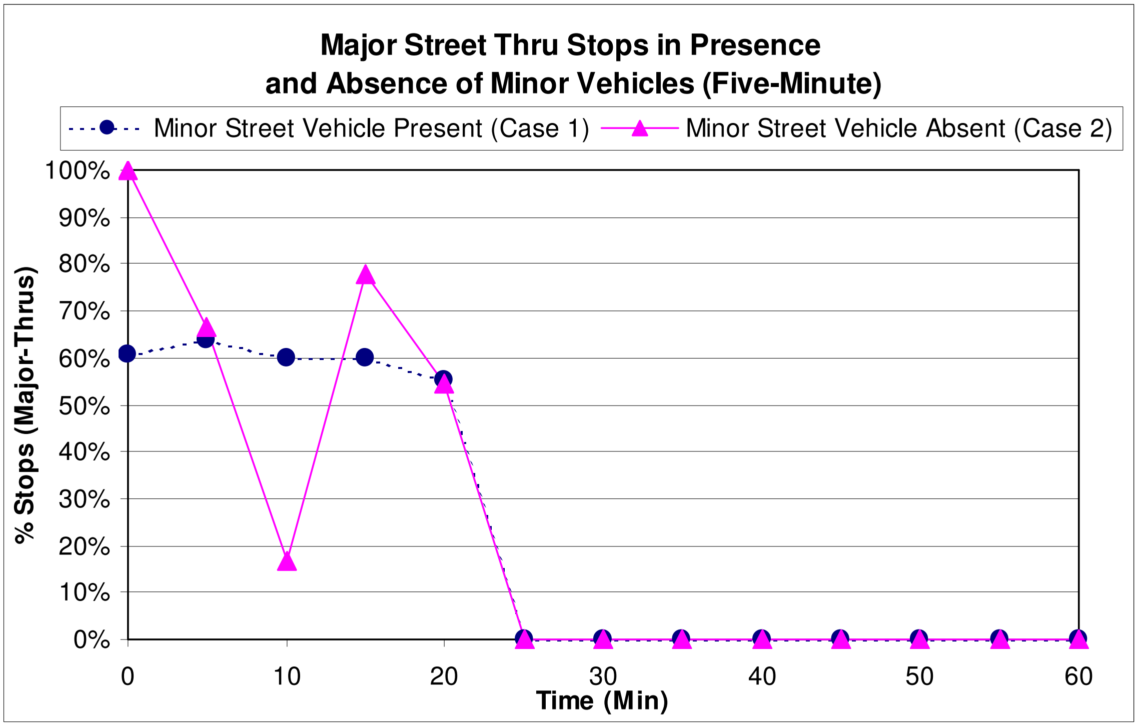


Figure G.4 One-Minute Presence and Absence Analysis at Monroe Dr./10th St.



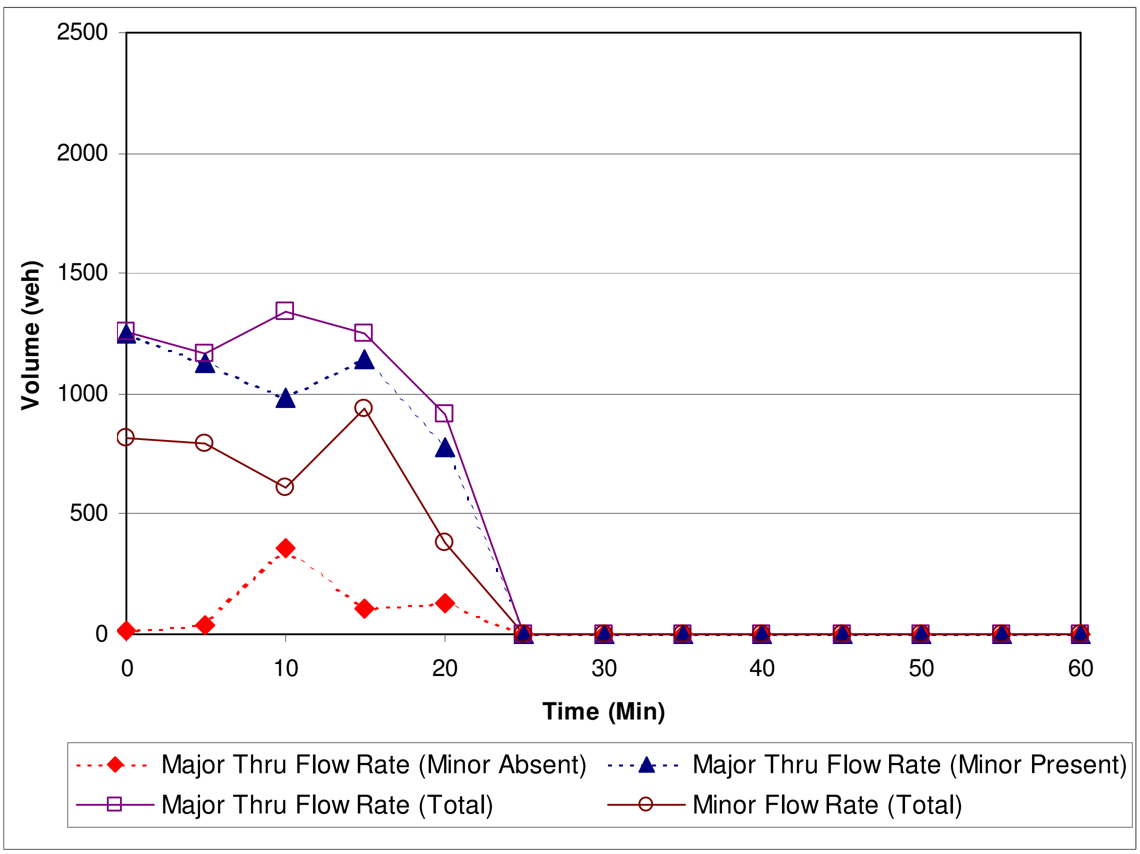
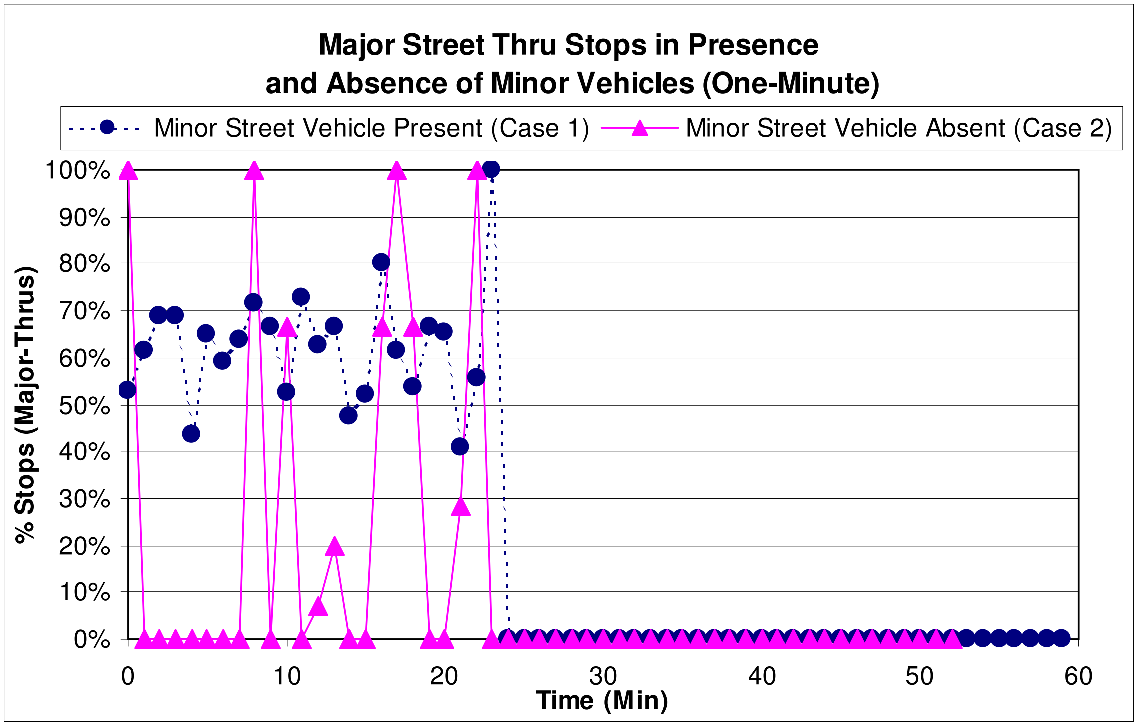


Figure G.5 Five-Minute Presence and Absence Analysis at Rainbow St./Candler Rd.



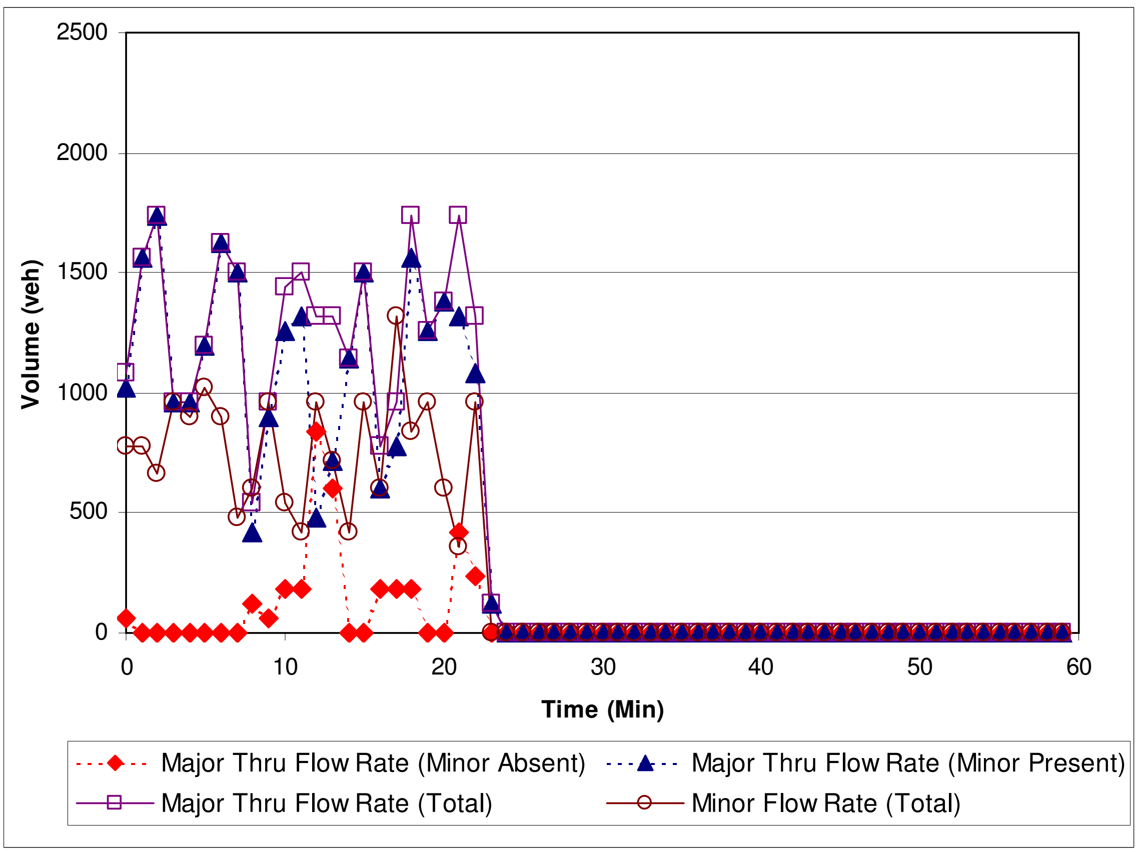


Figure G.6 One-Minute Presence and Absence Analysis at Rainbow St./Candler Rd.

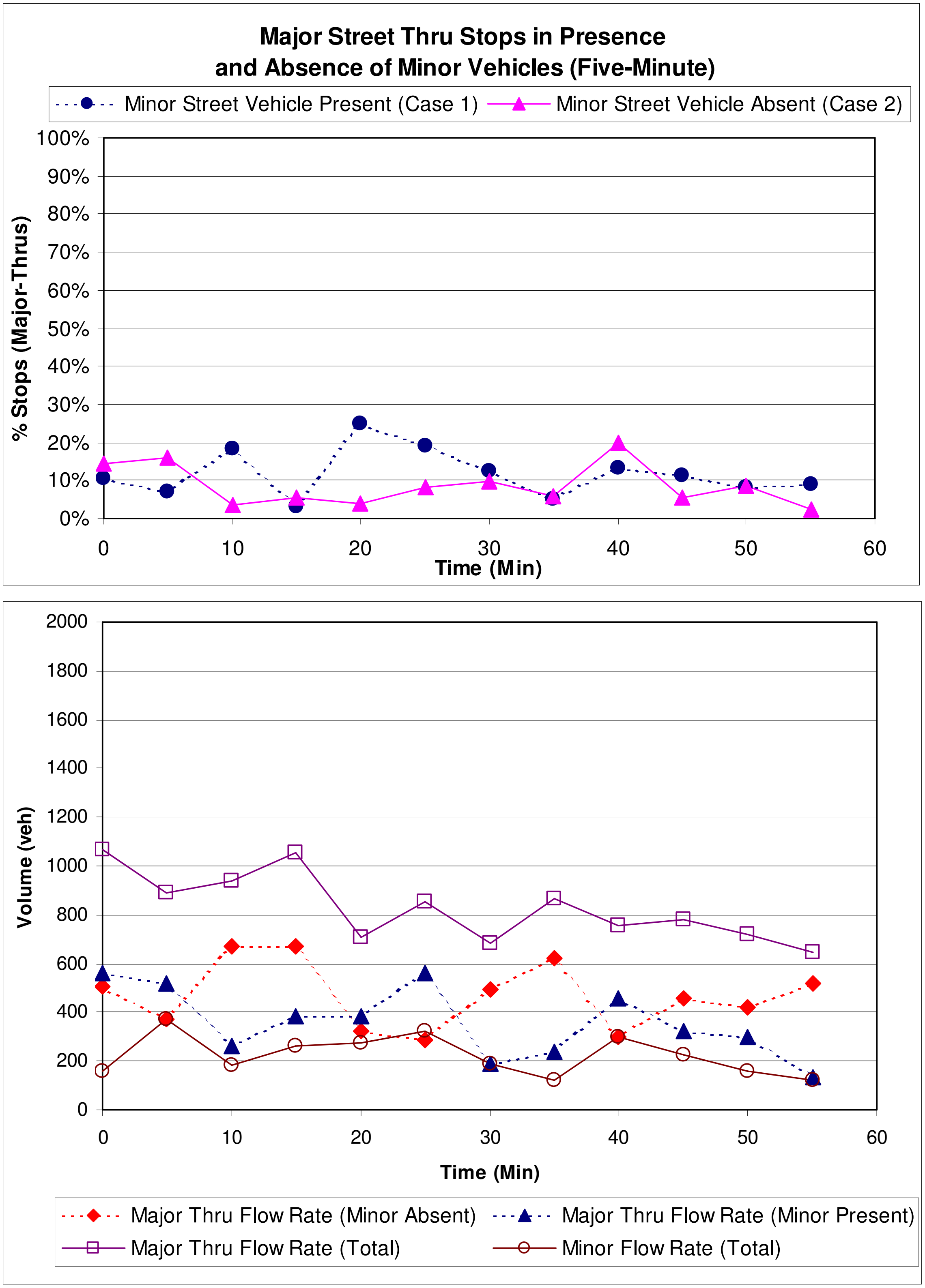
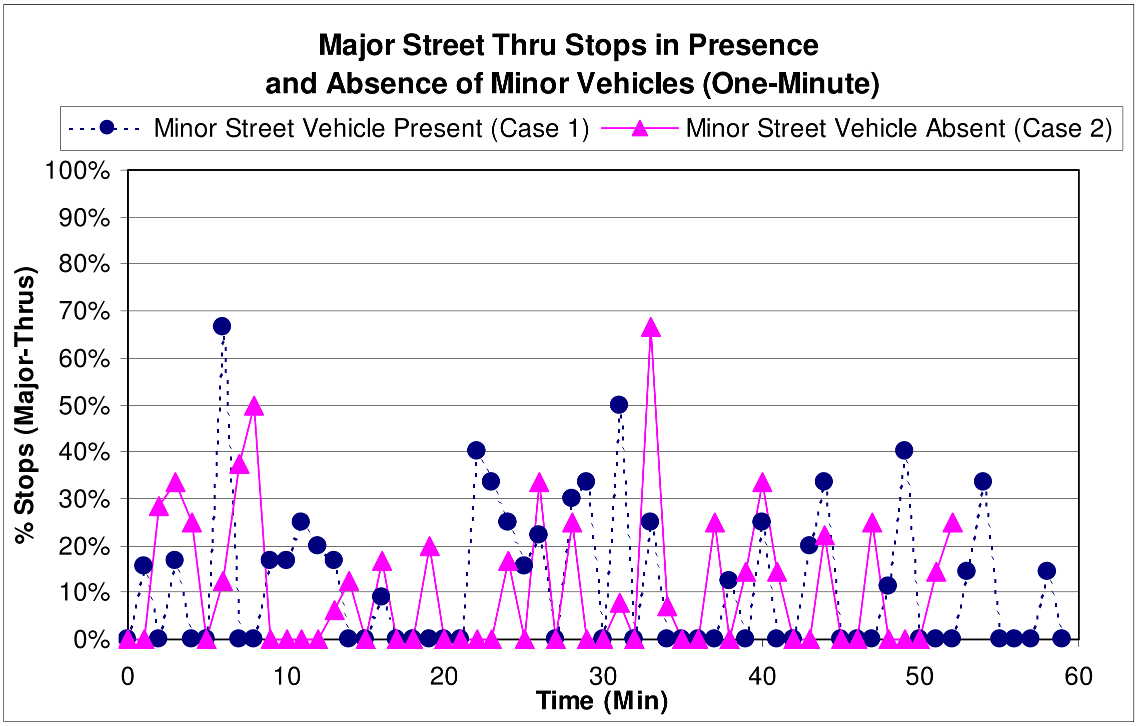


Figure G.7 Five-Minute Presence and Absence Analysis at N. Highland Ave./University Dr.



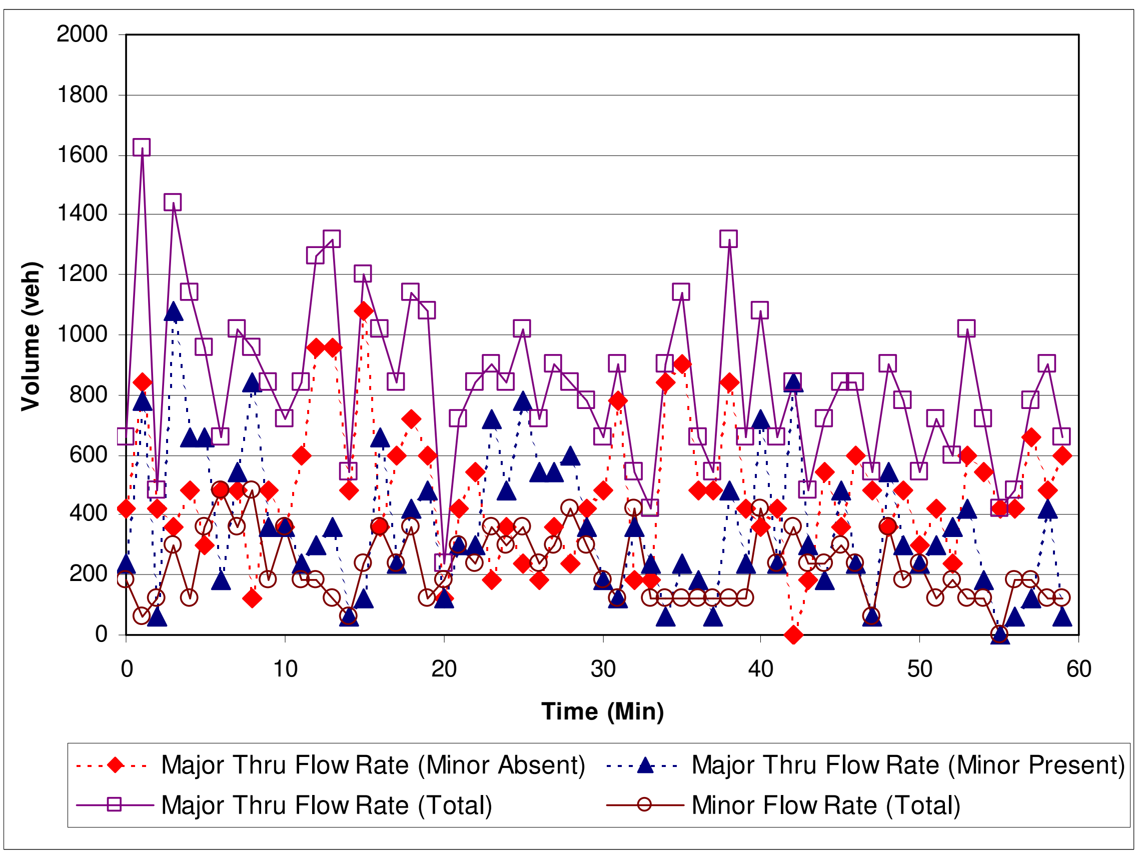
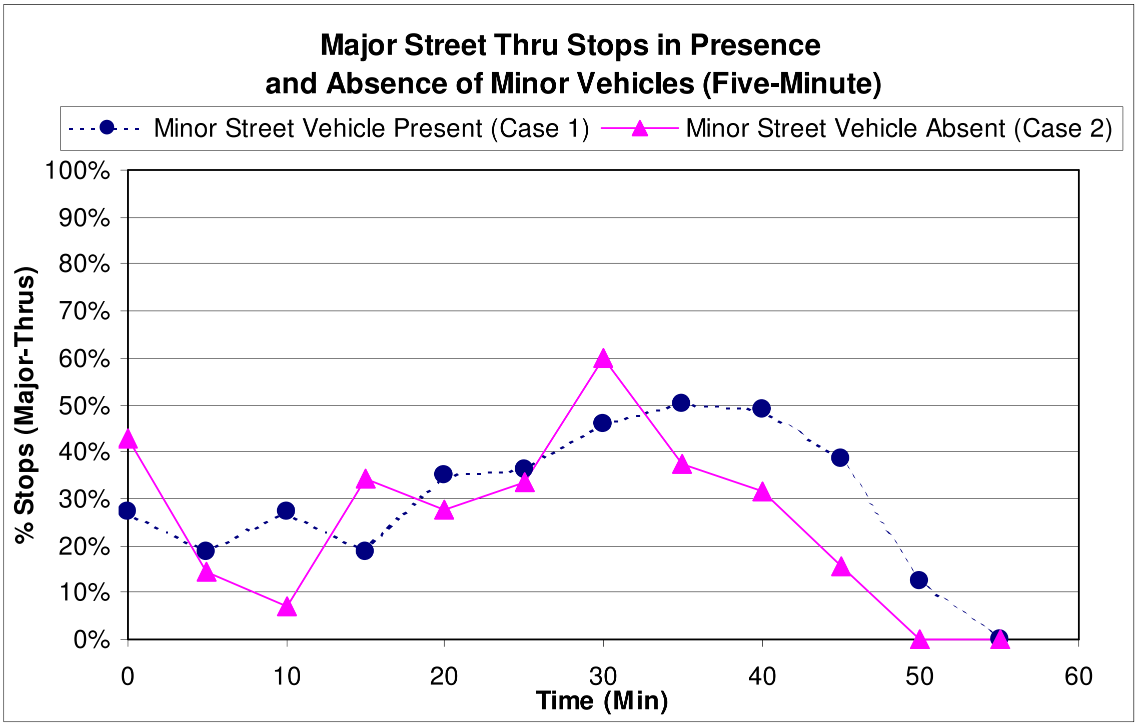


Figure G.8 One-Minute Presence and Absence Analysis at N. Highland Ave./University Dr.



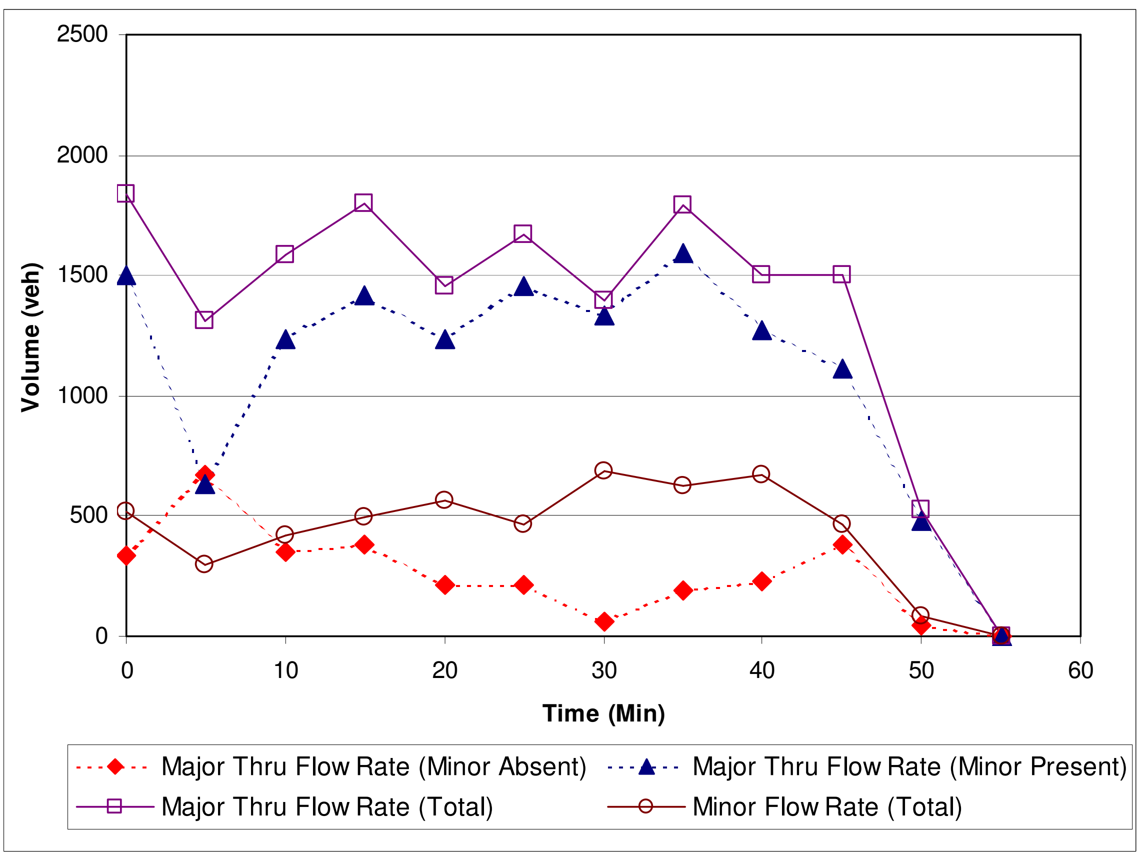
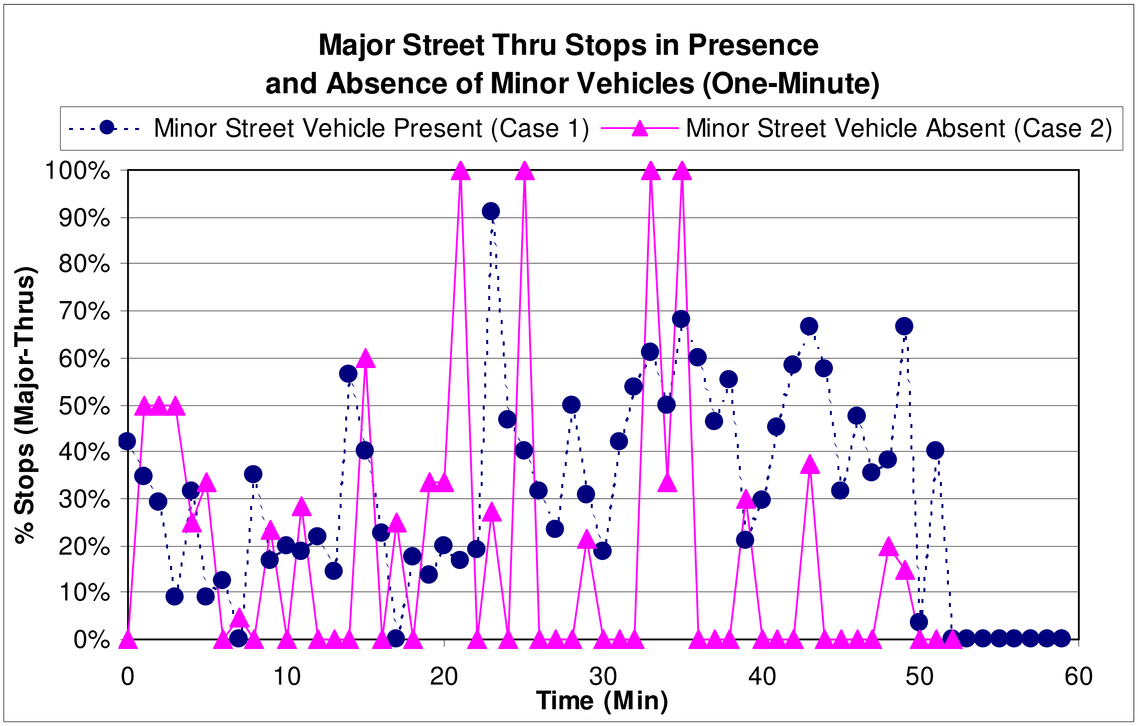


Figure G.9 Five-Minute Presence and Absence Analysis at Lenox Rd./Phipps Blvd.



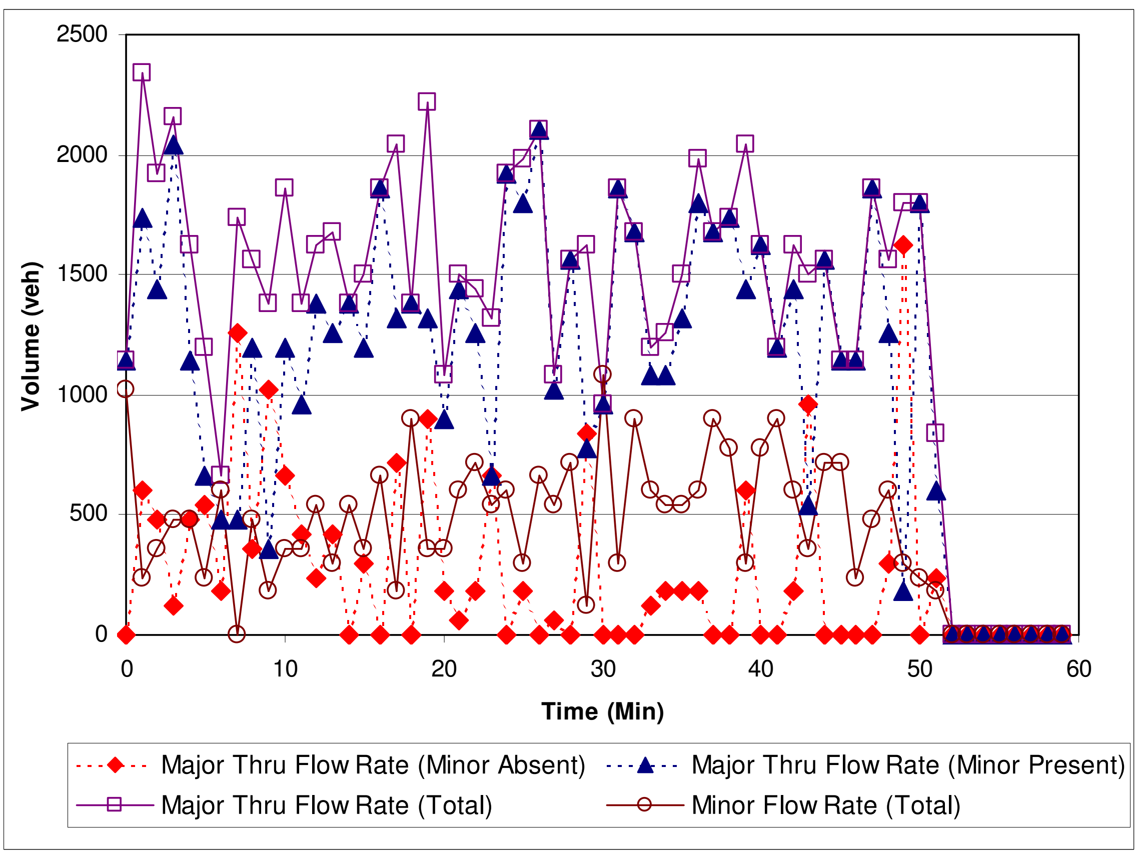
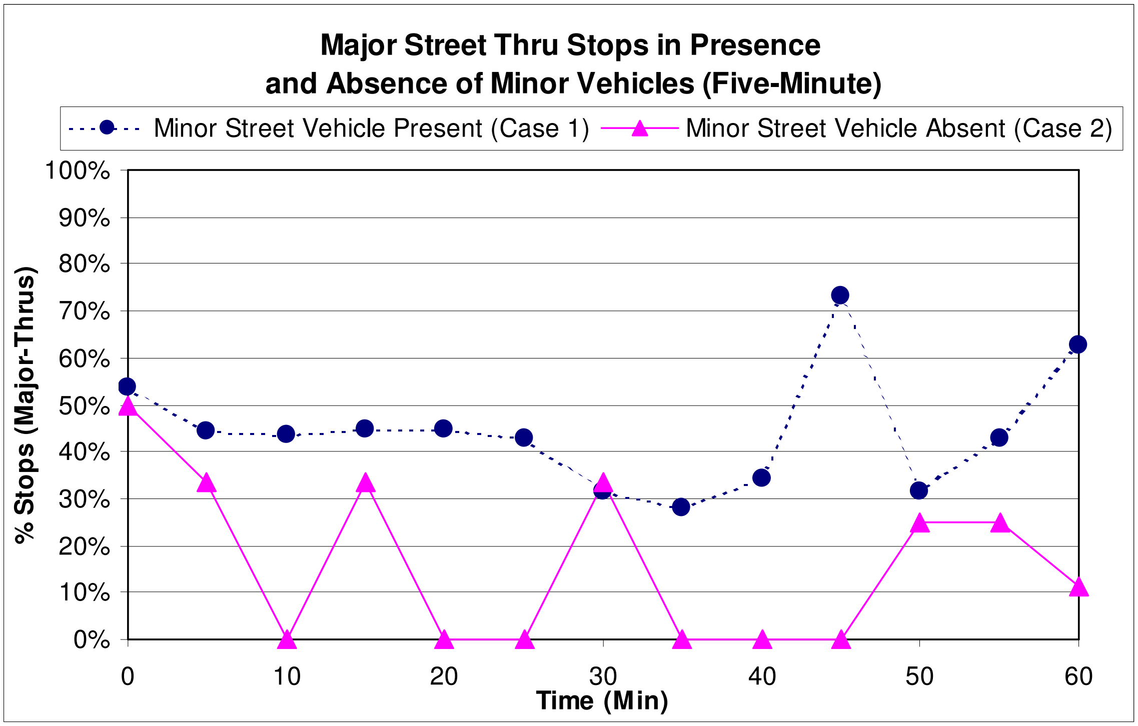


Figure G.10 One-Minute Presence and Absence Analysis at Lenox Rd./Phipps Blvd.



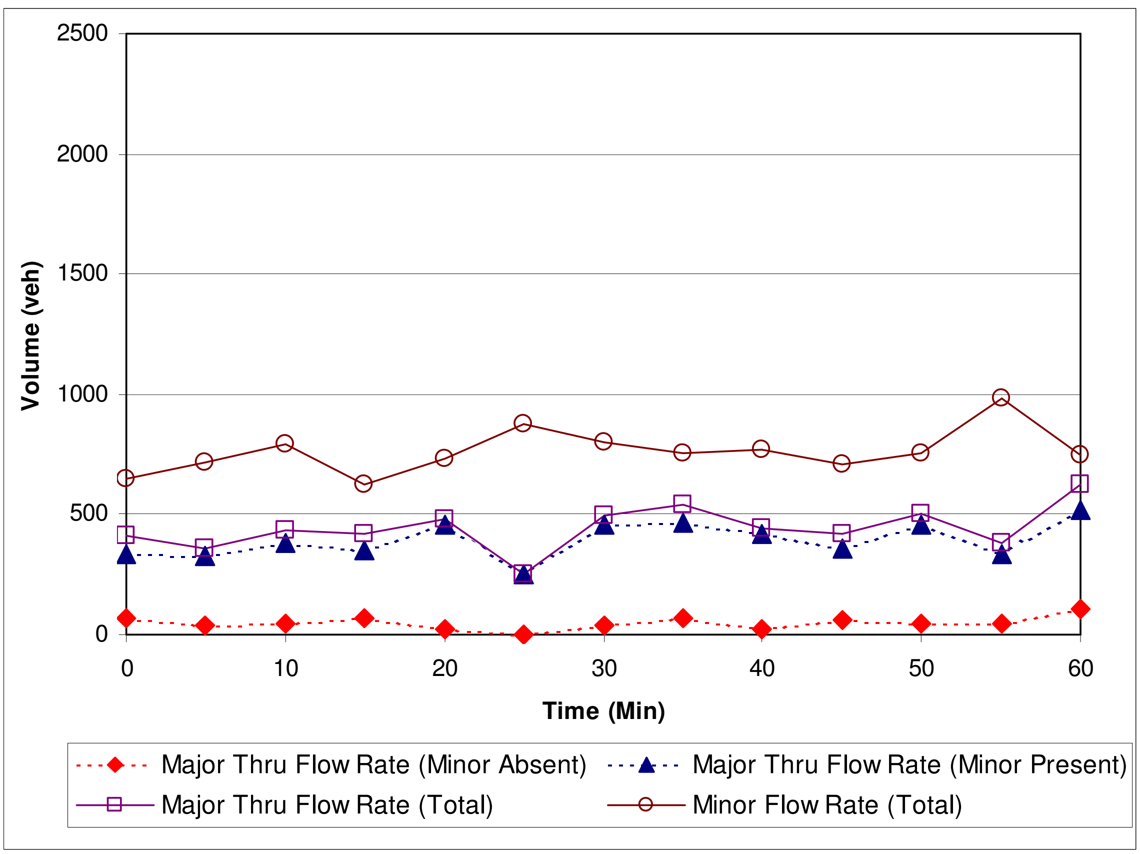
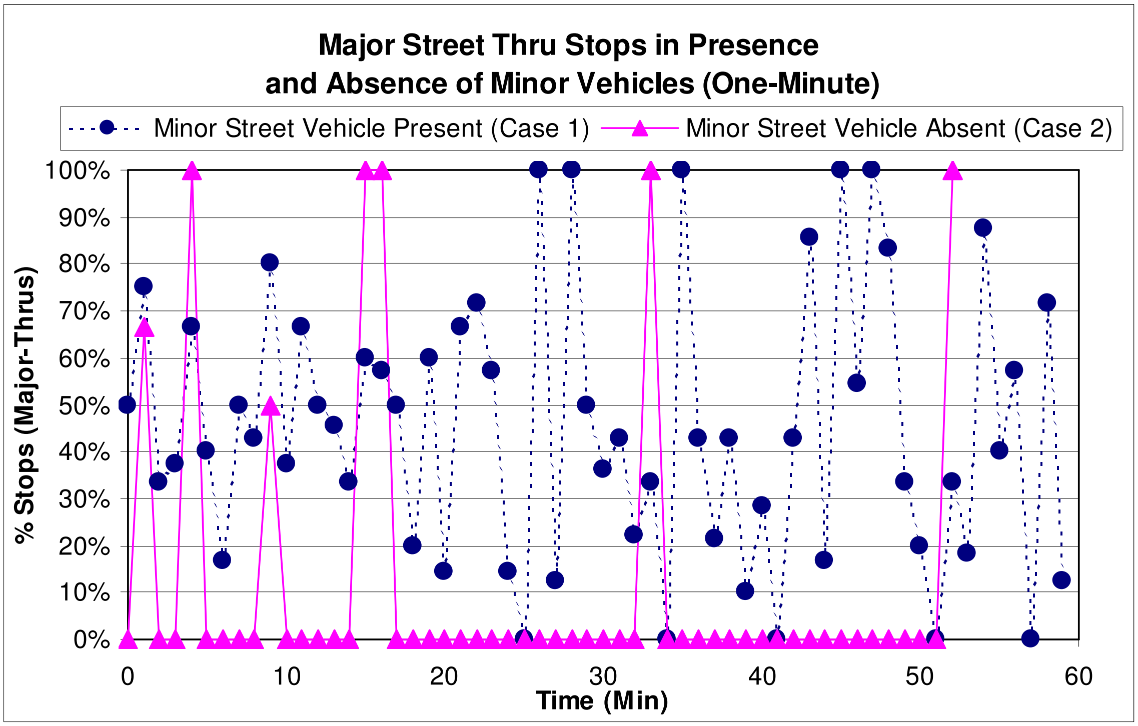


Figure G.11 Five-Minute Presence and Absence Analysis at Spring St./17th St.



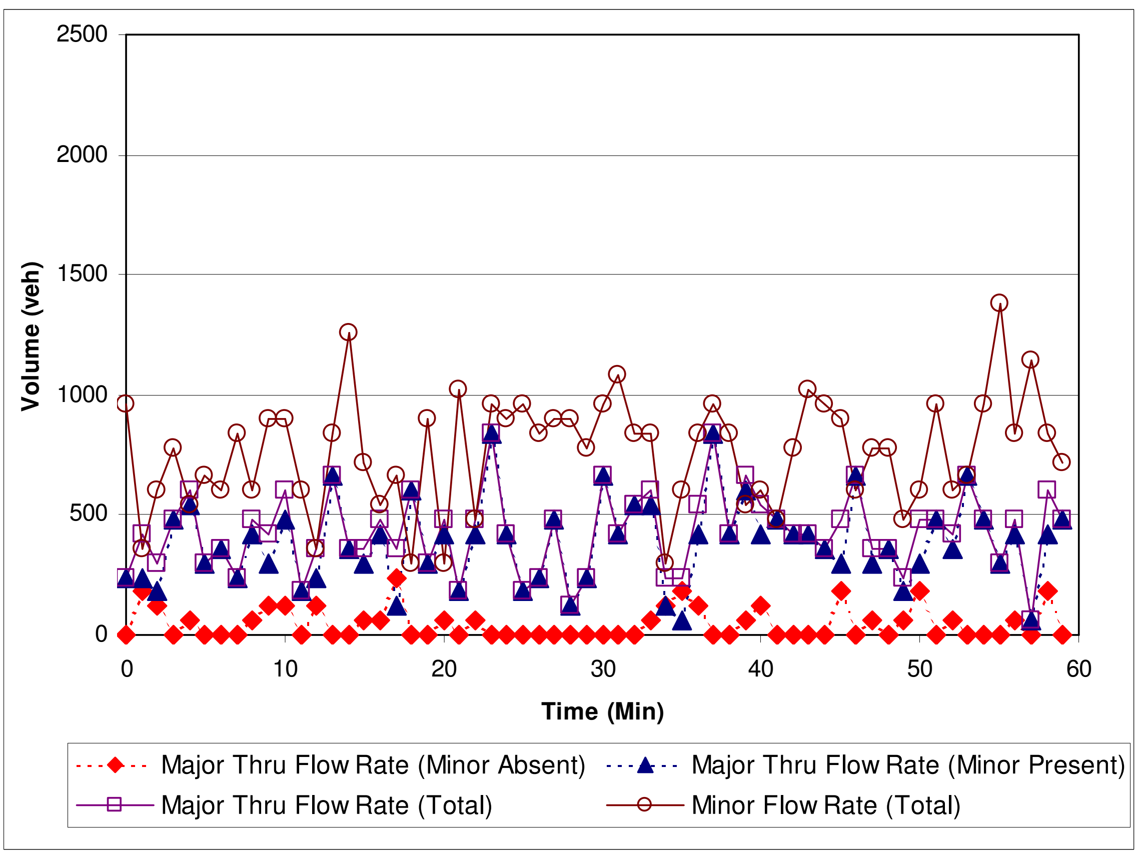


Figure G.12 One-Minute Presence and Absence Analysis at Spring St./17th St.

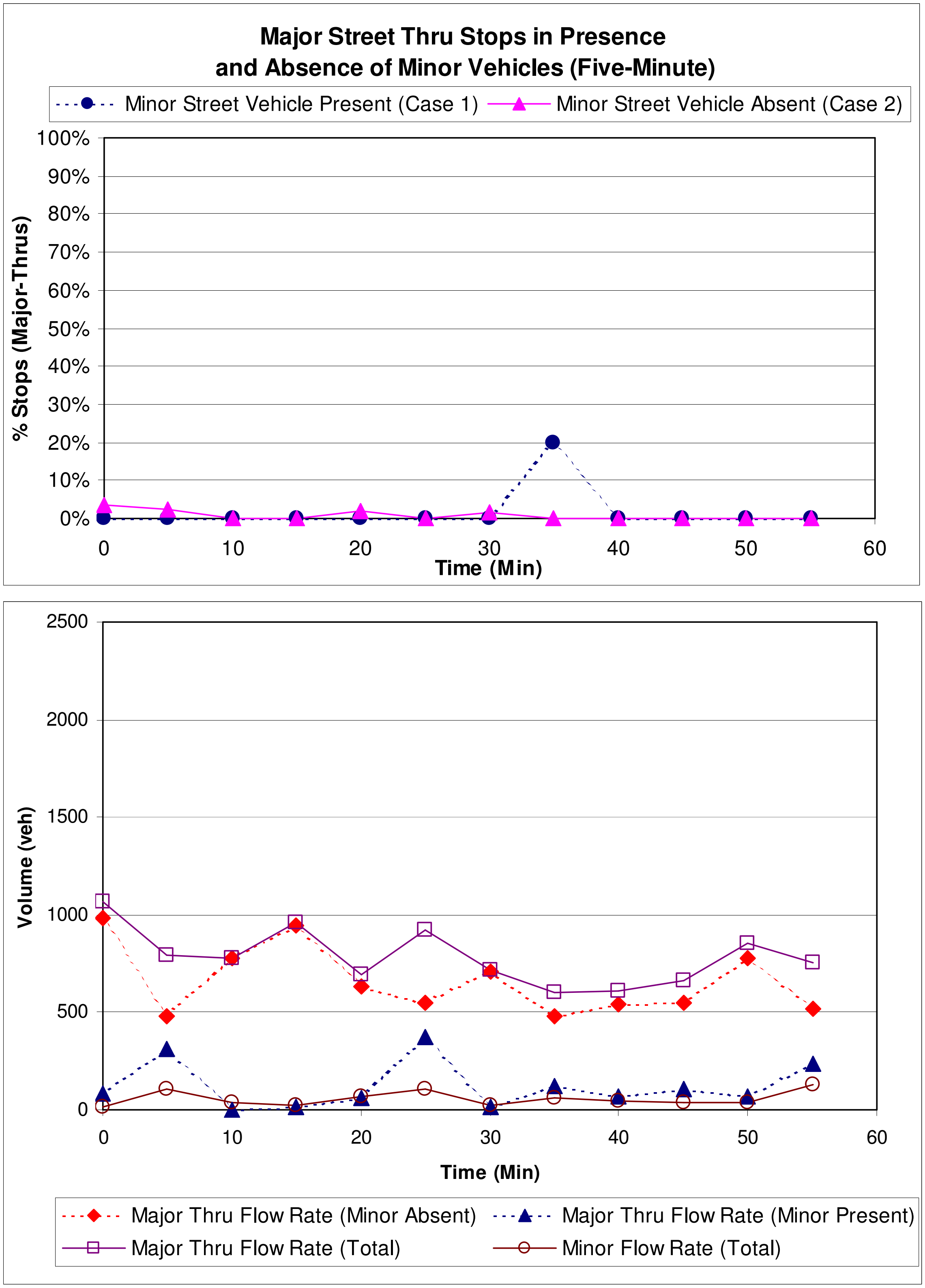
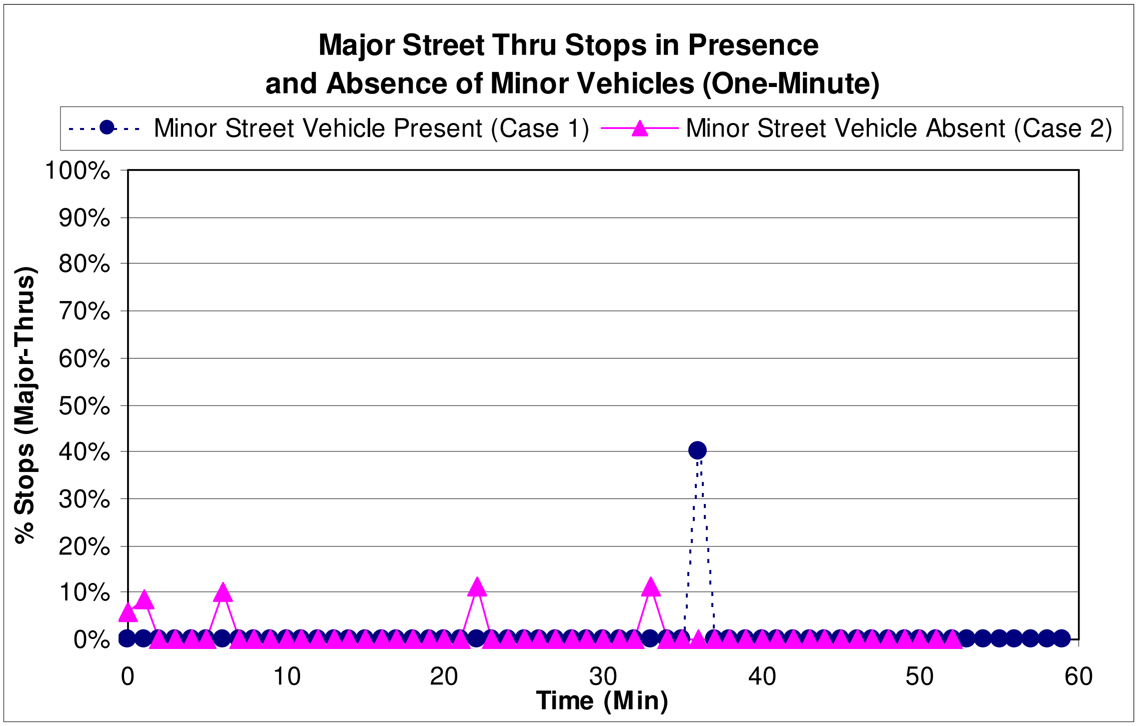


Figure G.13 Five-Minute Presence and Absence Analysis at W. Peachtree St./11th St.



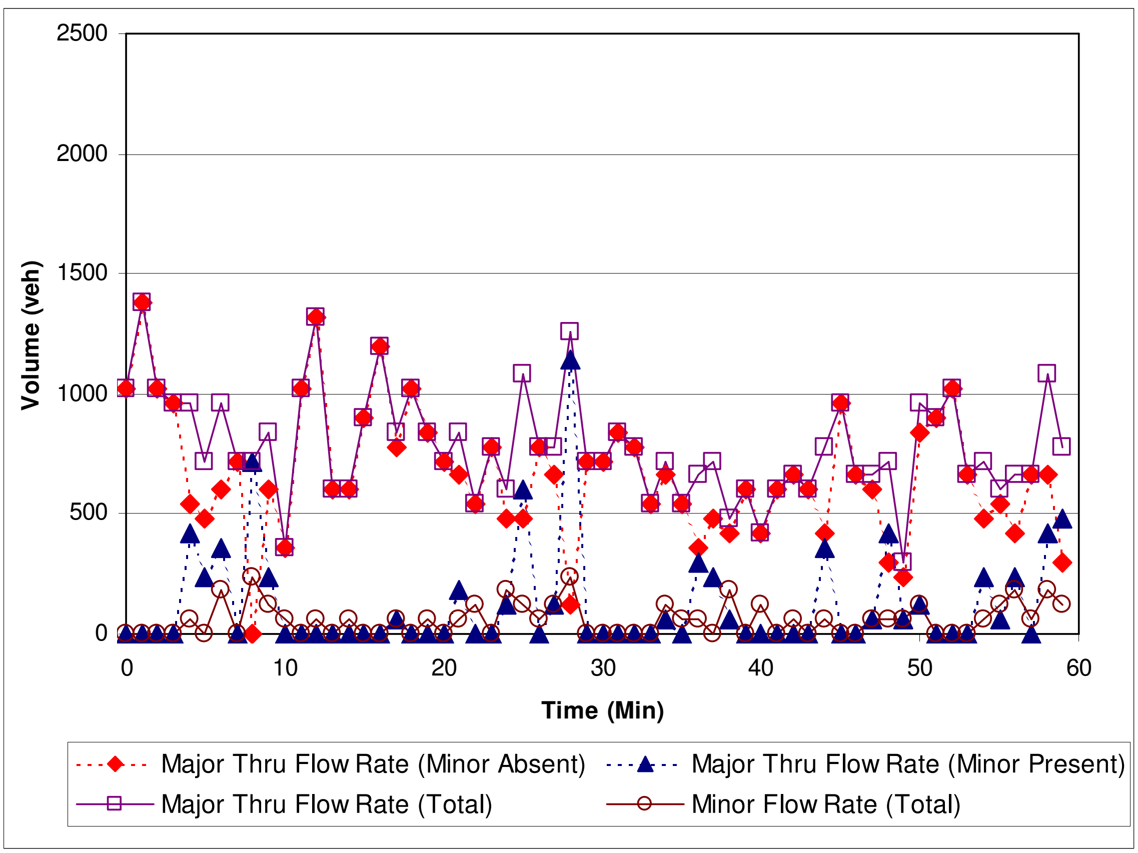
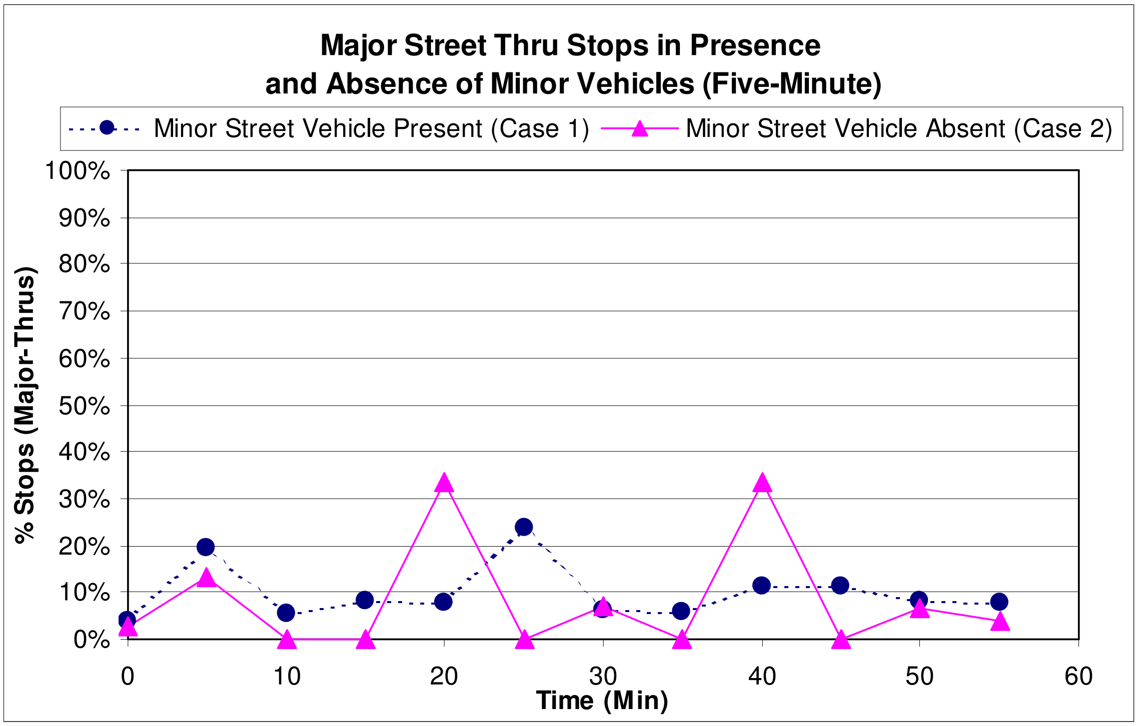


Figure G.14 One-Minute Presence and Absence Analysis at W. Peachtree St./11th St.



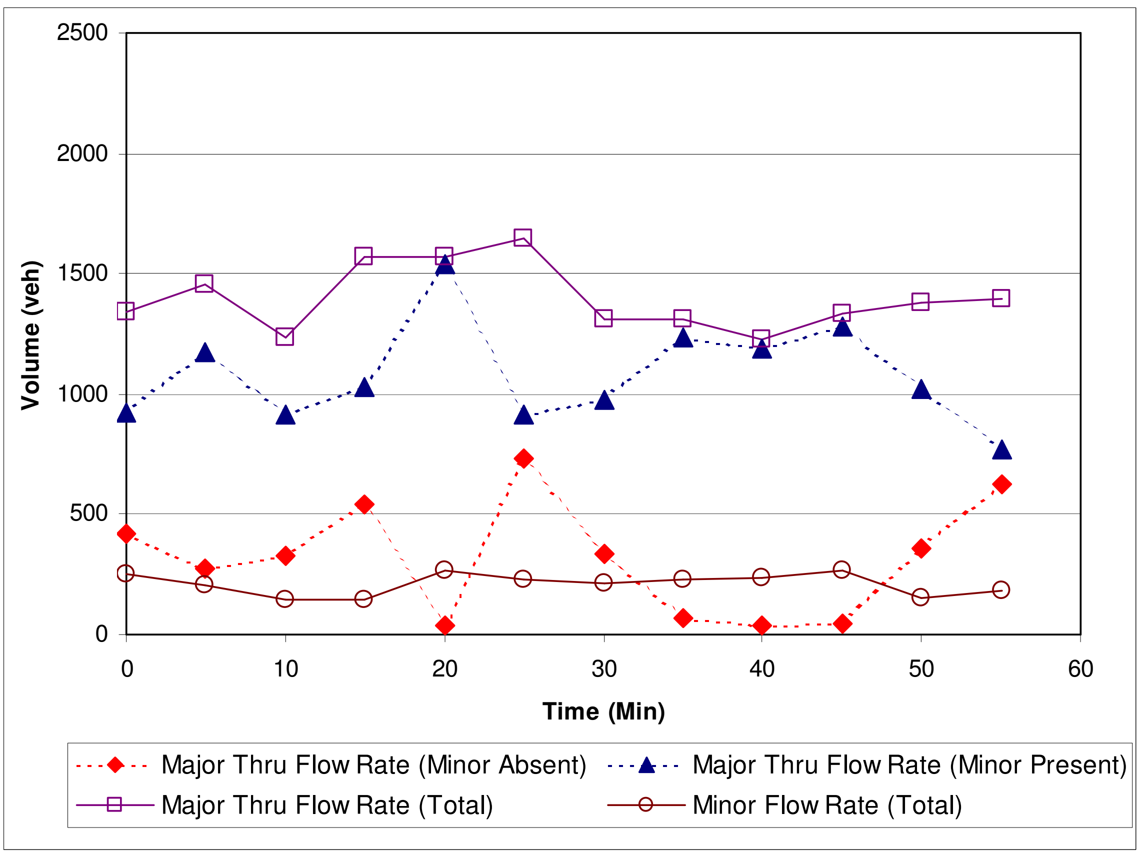
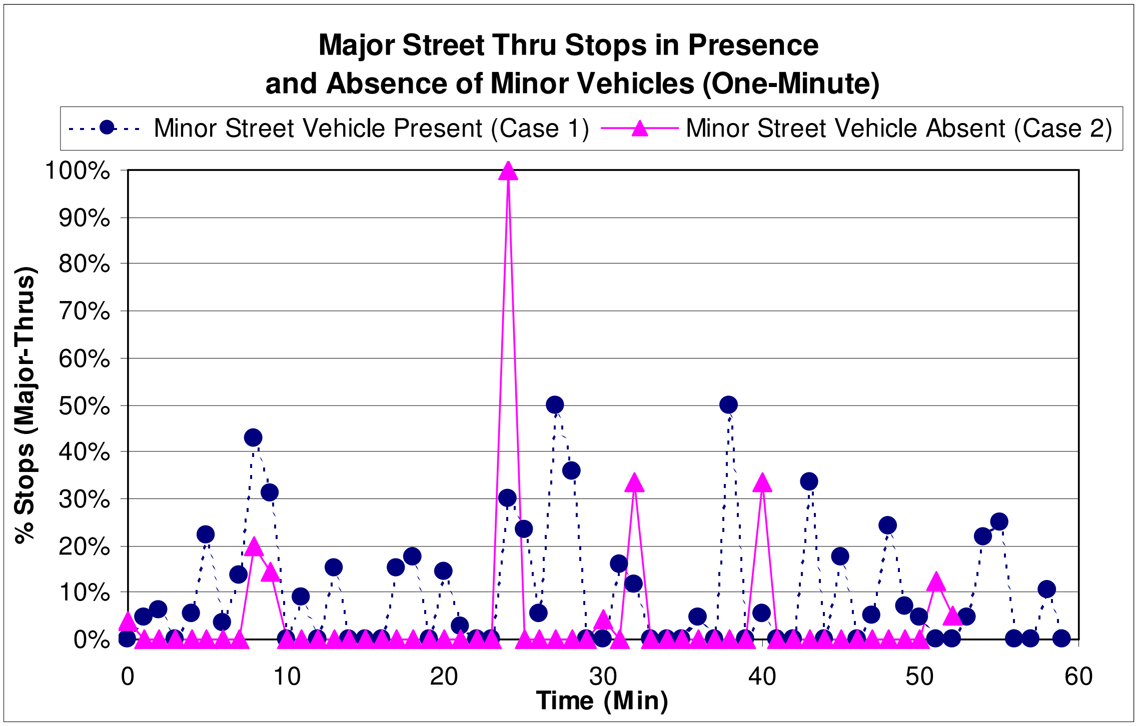


Figure G.15 Five-Minute Presence and Absence Analysis at W. Peachtree St./16th St.



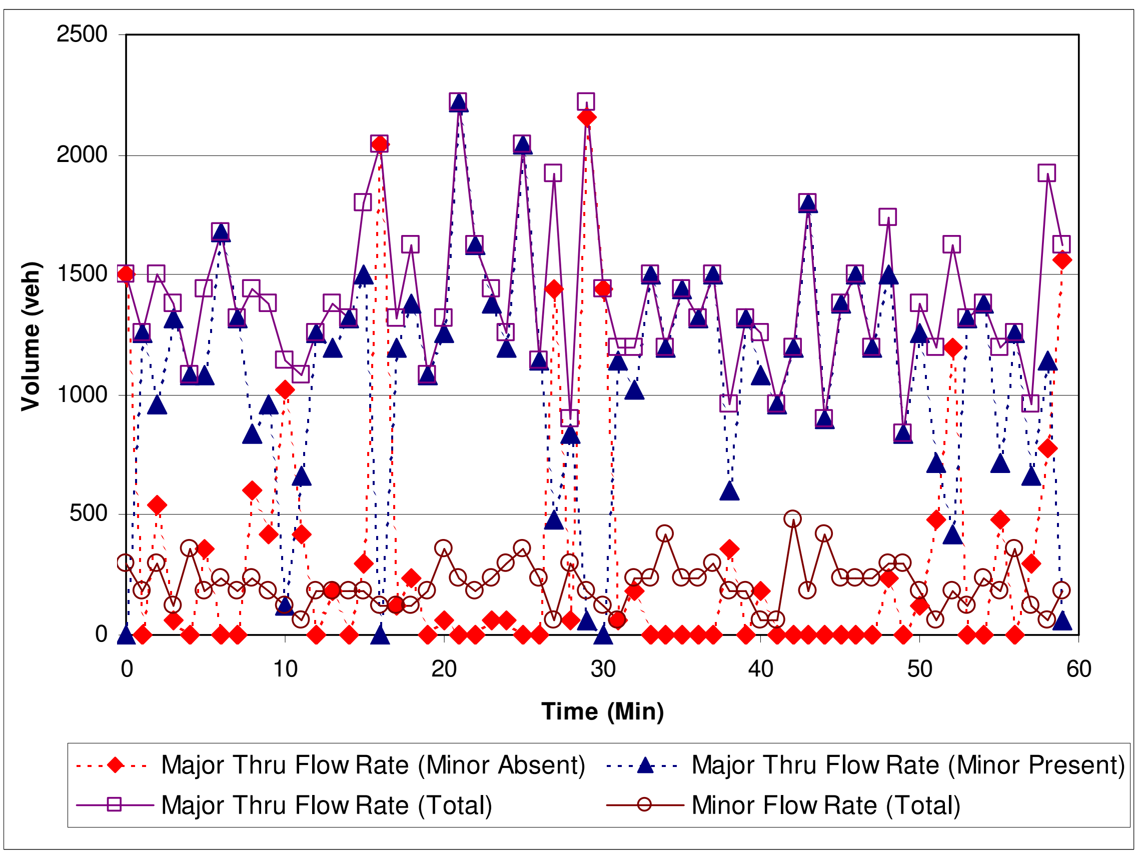


Figure G.16 One-Minute Presence and Absence Analysis at W. Peachtree St./16th St.

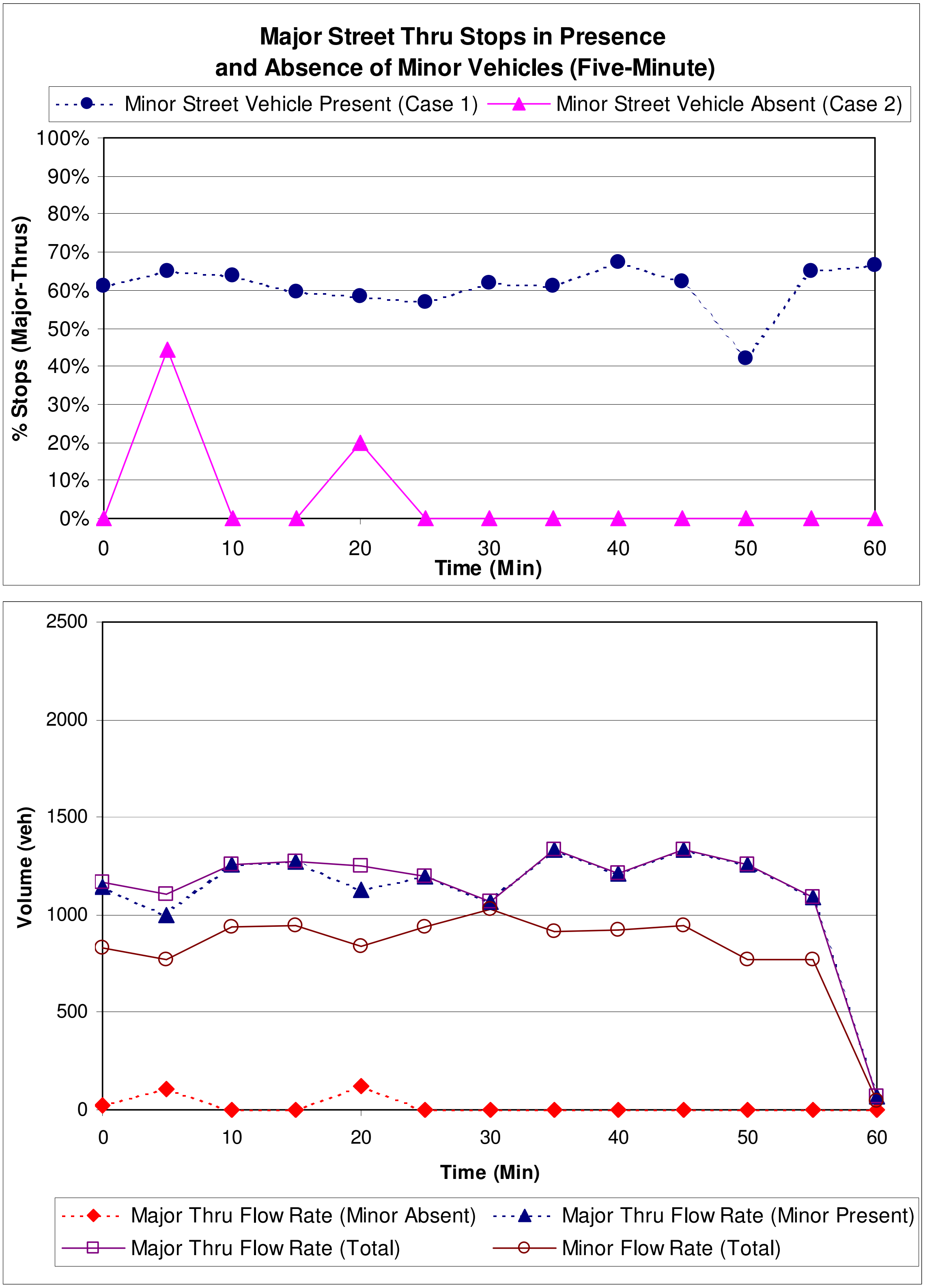


Figure G.17 Five-Minute Presence and Absence Analysis at 14th St./Williams St.

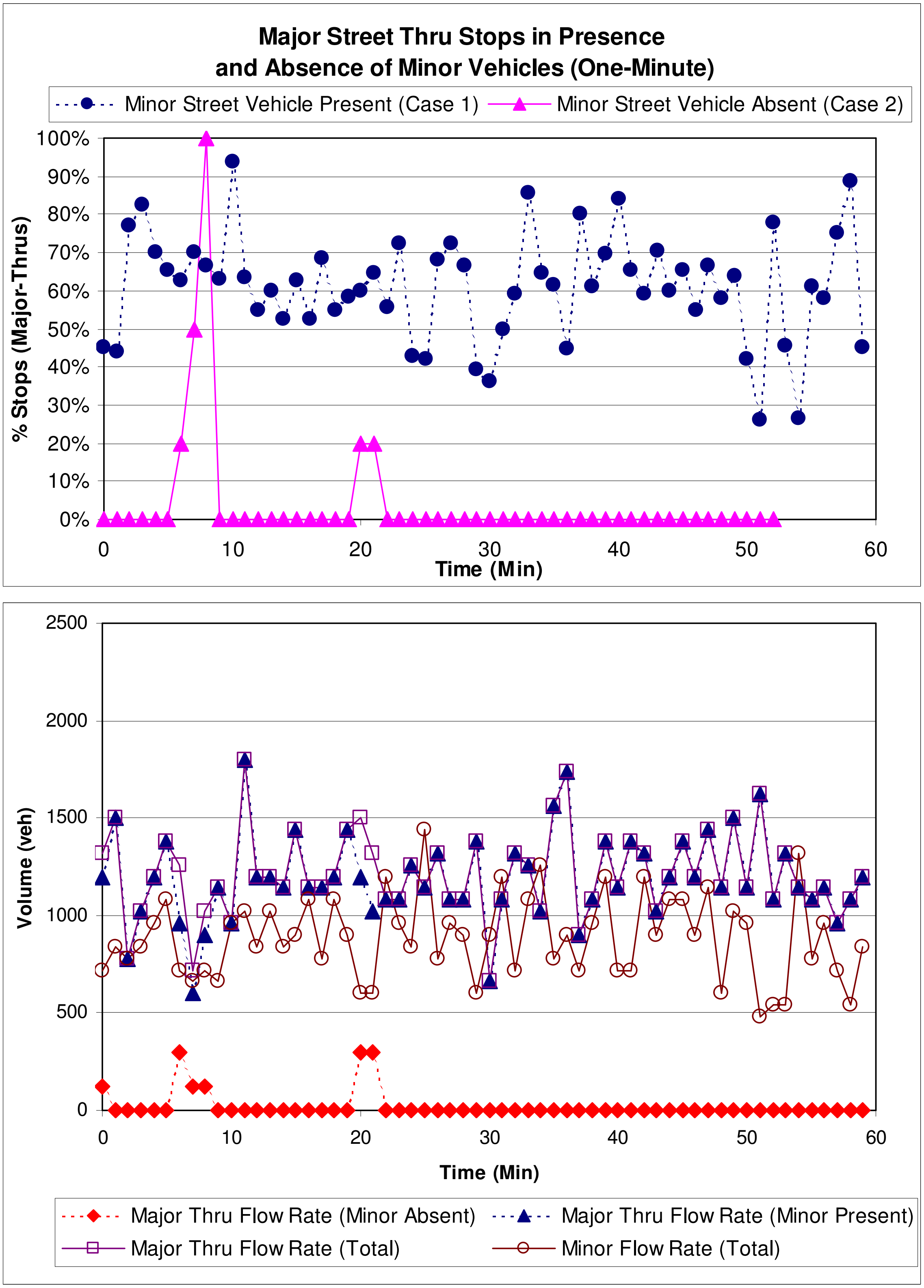
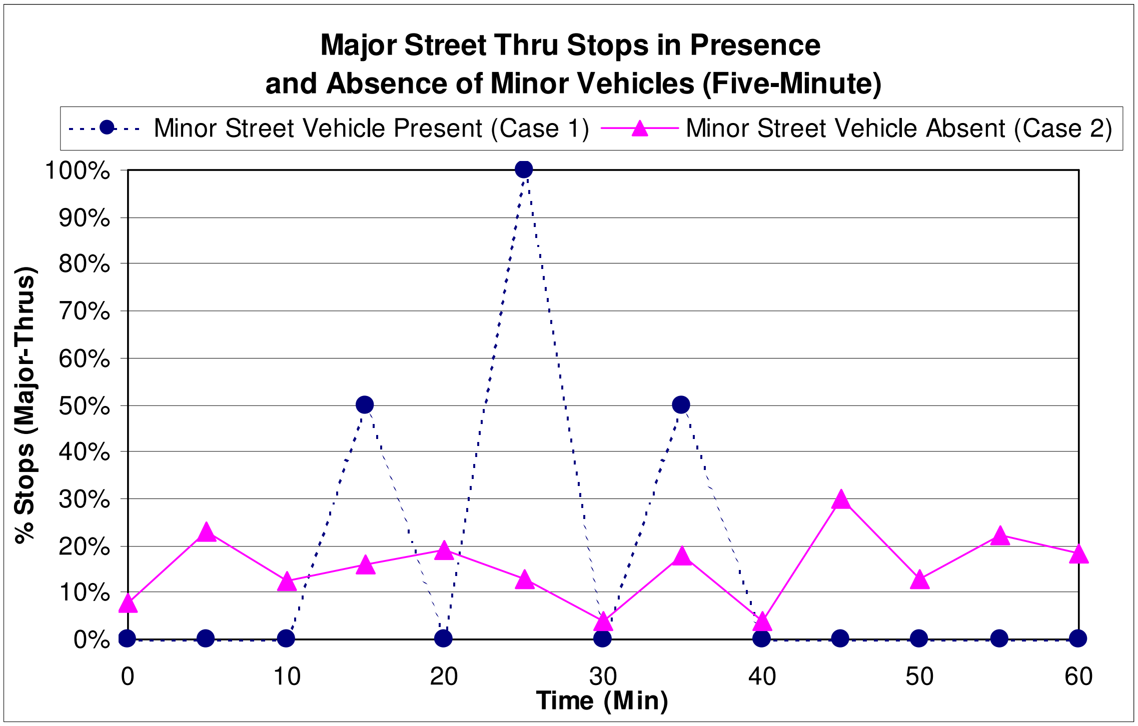


Figure G.18 One-Minute Presence and Absence Analysis at 14th St./Williams St.



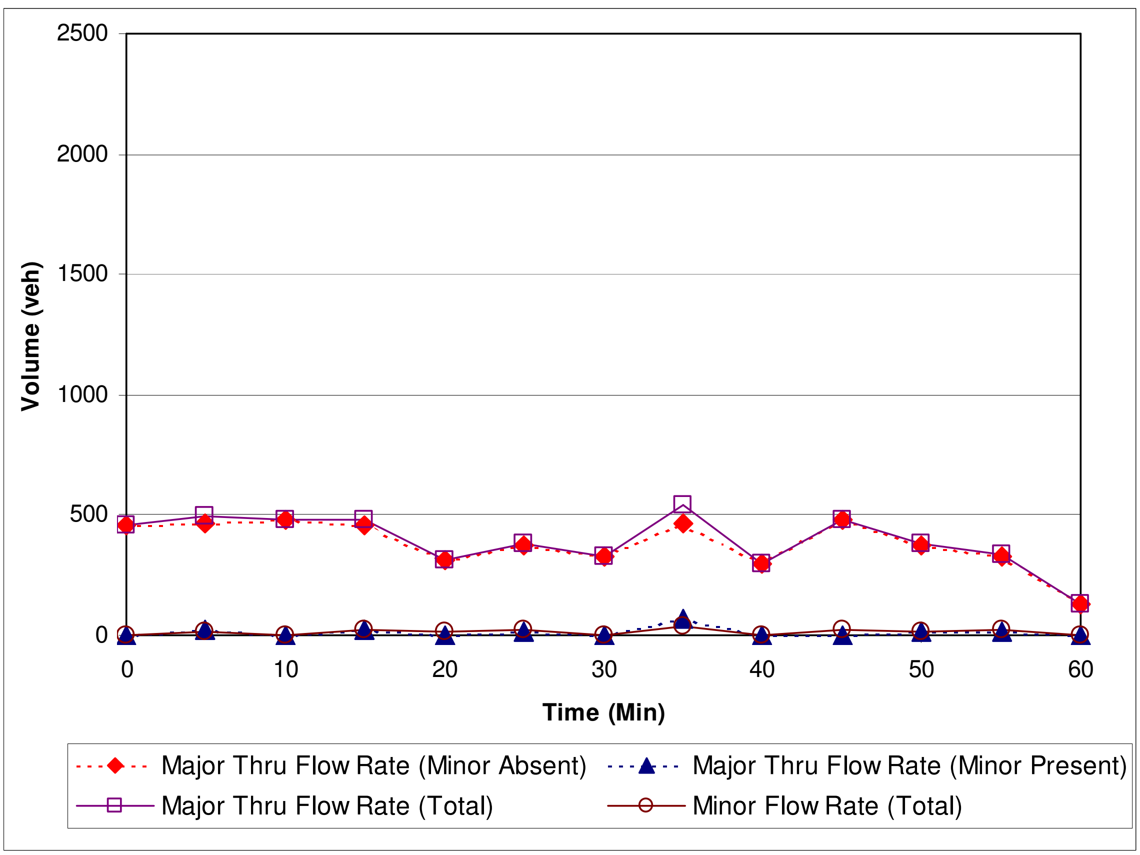
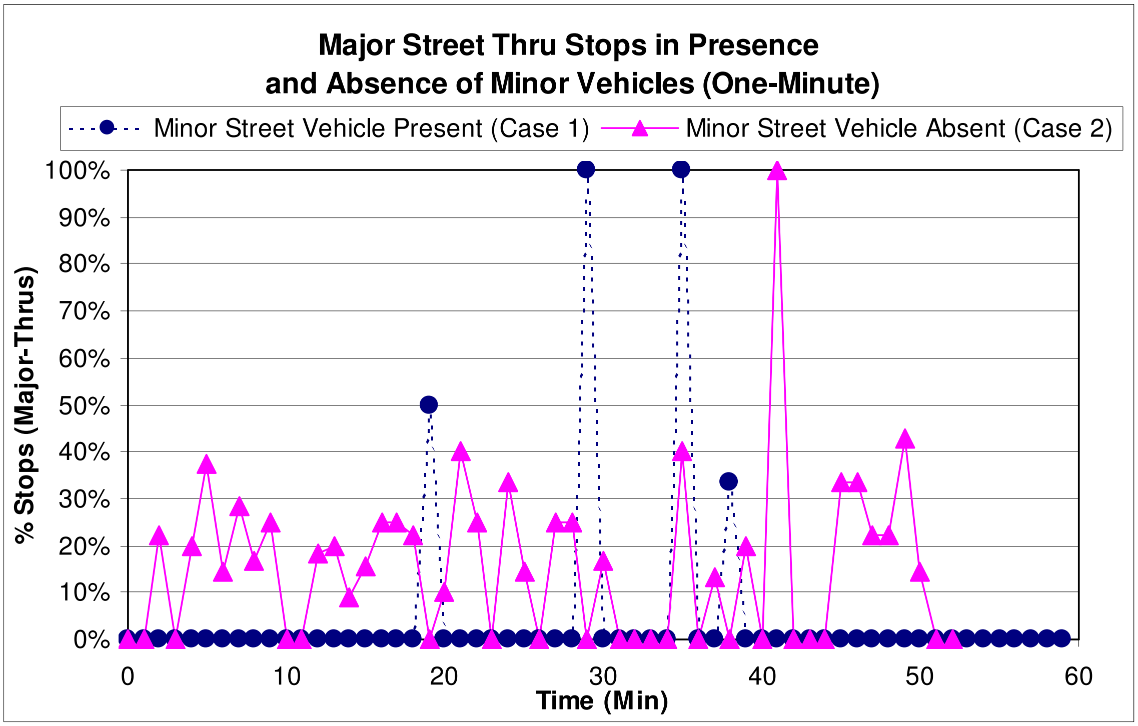


Figure G.19 Five-Minute Presence and Absence Analysis at Market St./16th St.



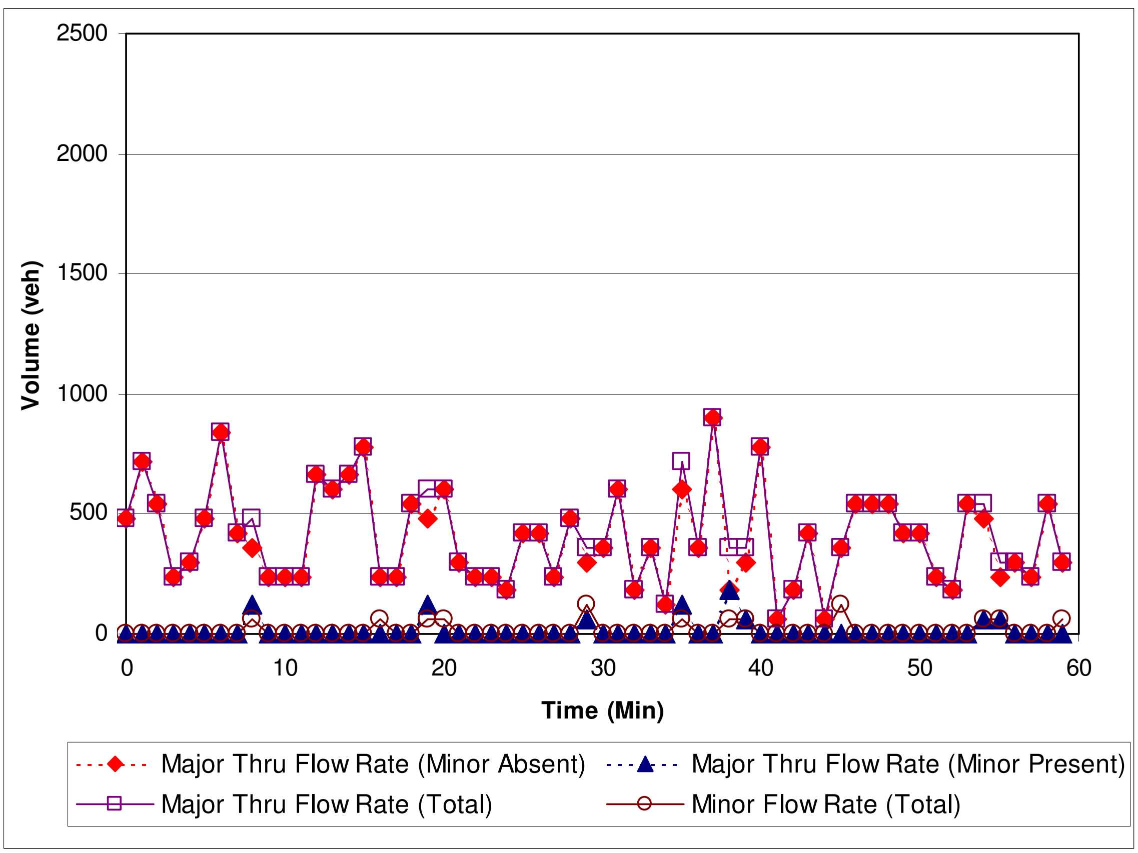
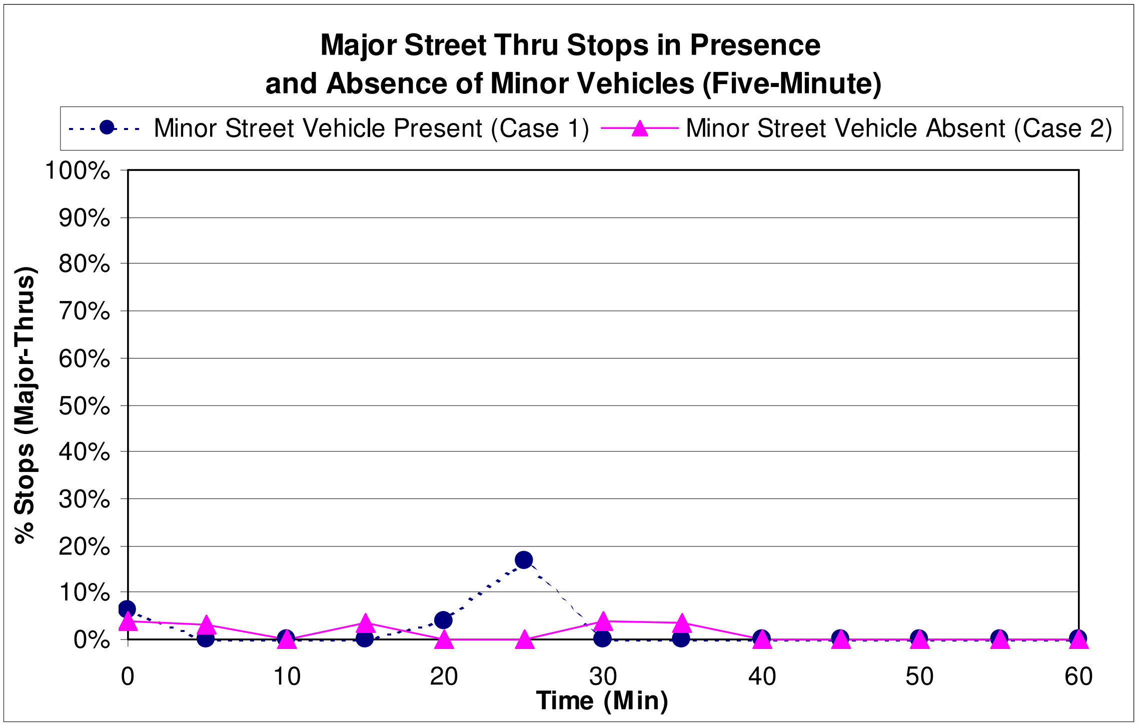


Figure G.20 One-Minute Presence and Absence Analysis at Market St./16th St.



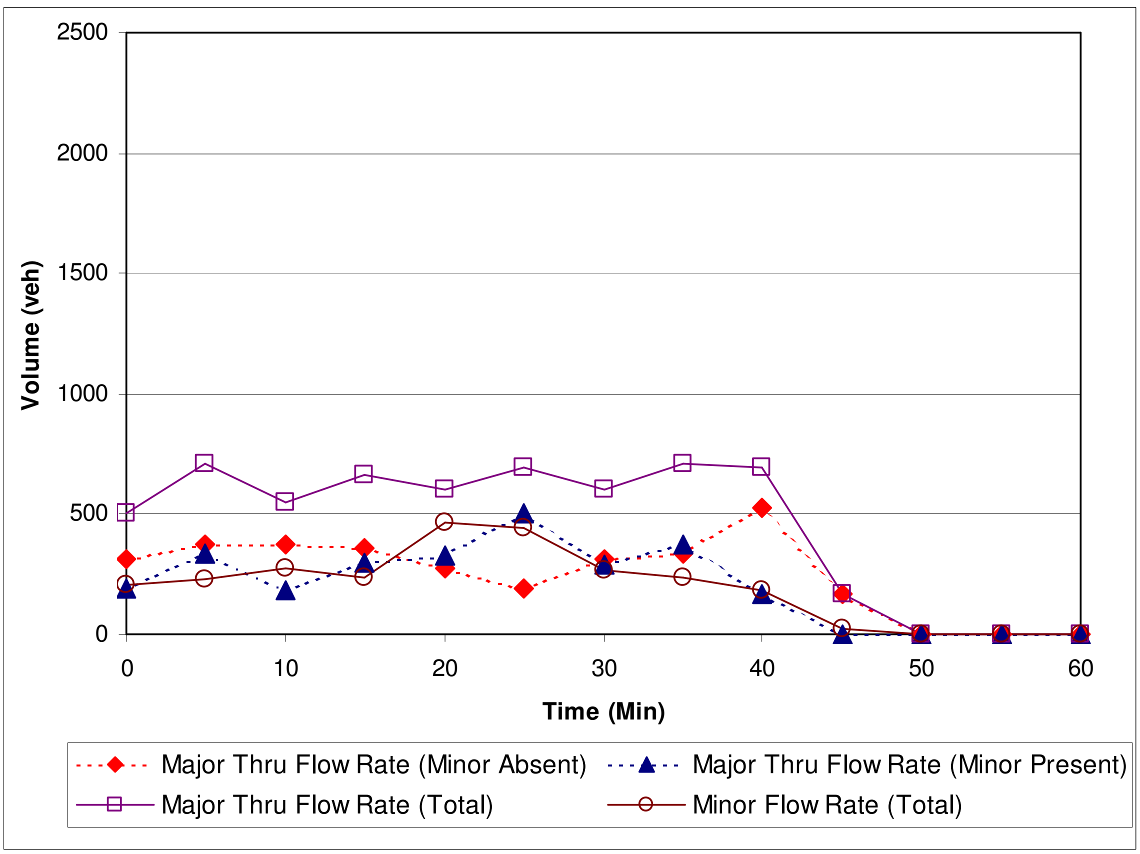
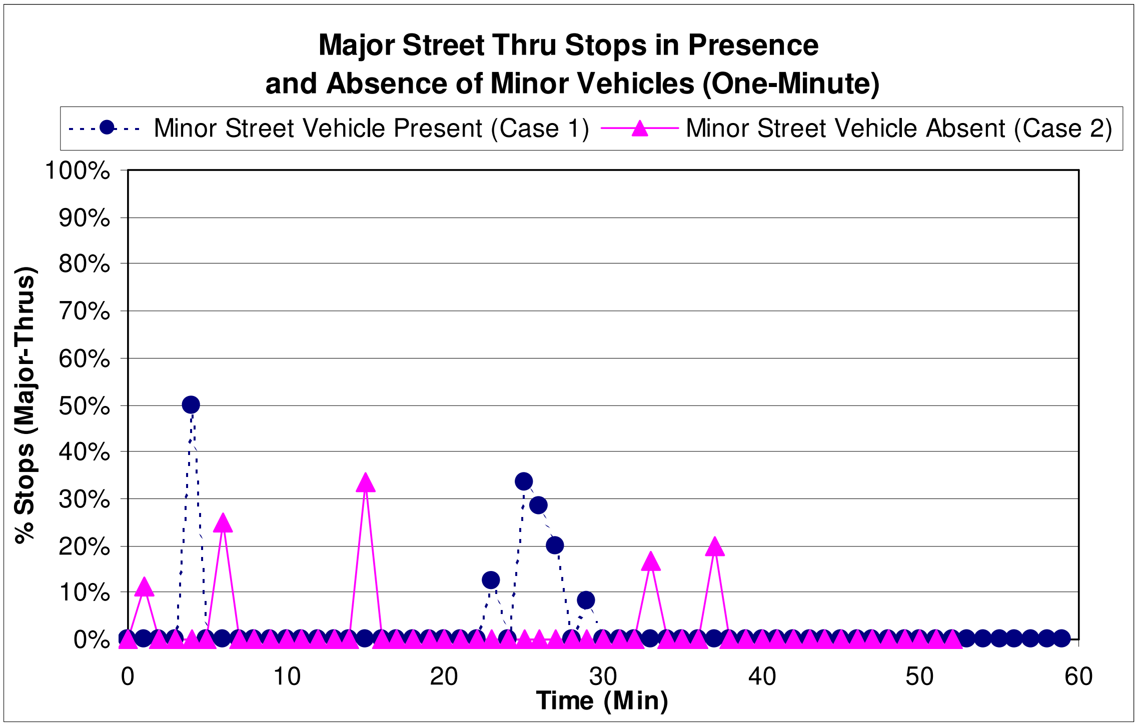


Figure G.21 Five-Minute Presence and Absence Analysis at 17th St./Bishop St.



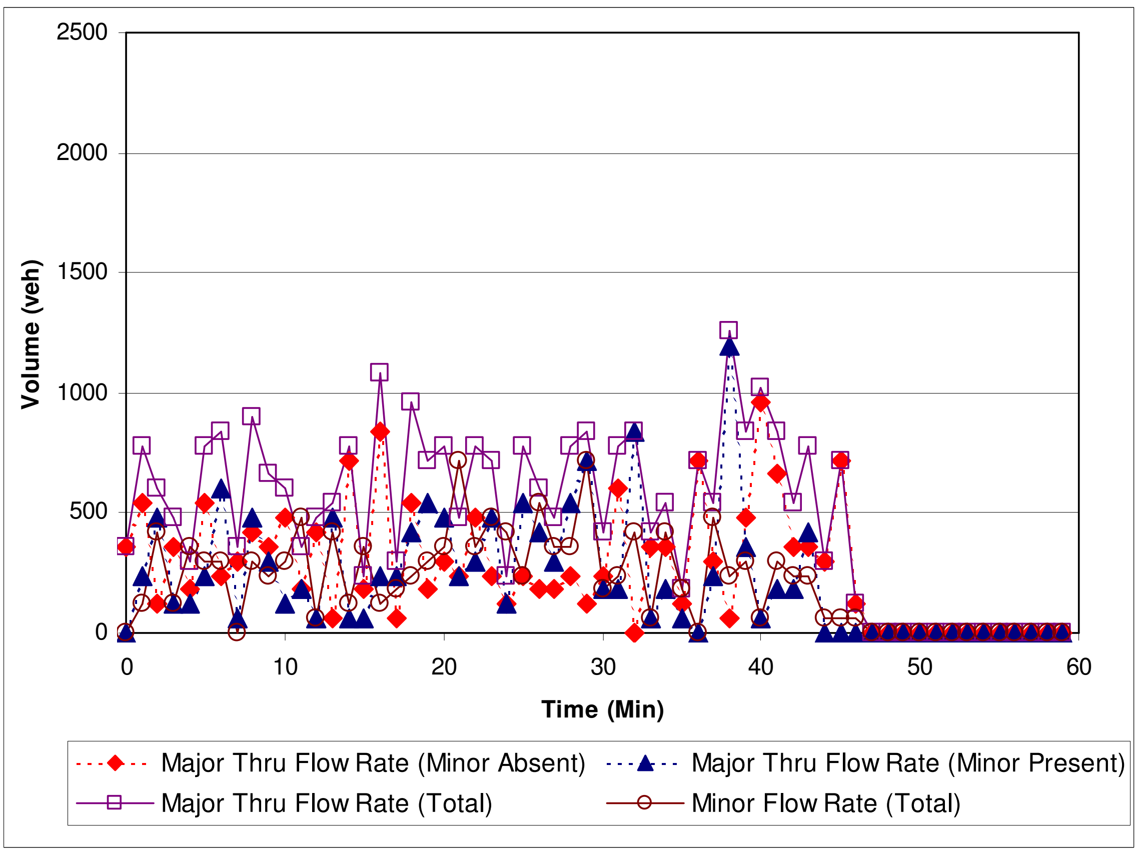
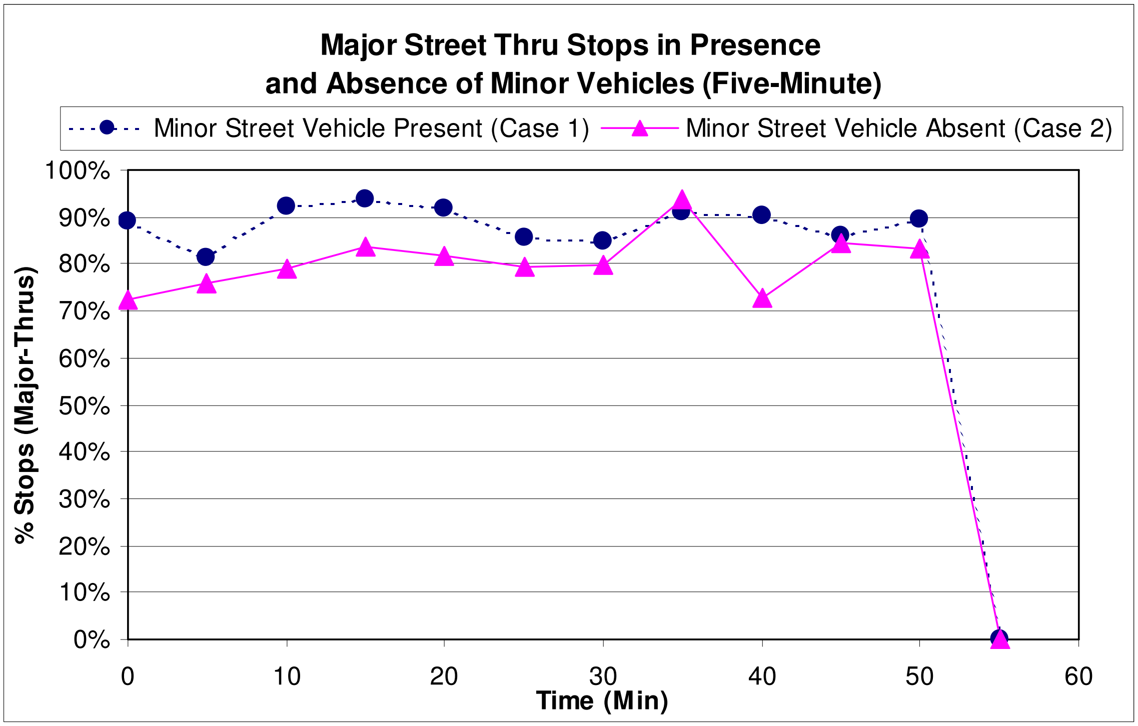


Figure G.22 One-Minute Presence and Absence Analysis at 17th St./Bishop St.

APPENDIX H

ONE- AND FIVE-MINUTE MAJOR STREET THRU STOPS IN THE PRESENCE AND ABSENCE OF MINOR STREET VEHICLES AT RED/RED FLASHING SIGNALS



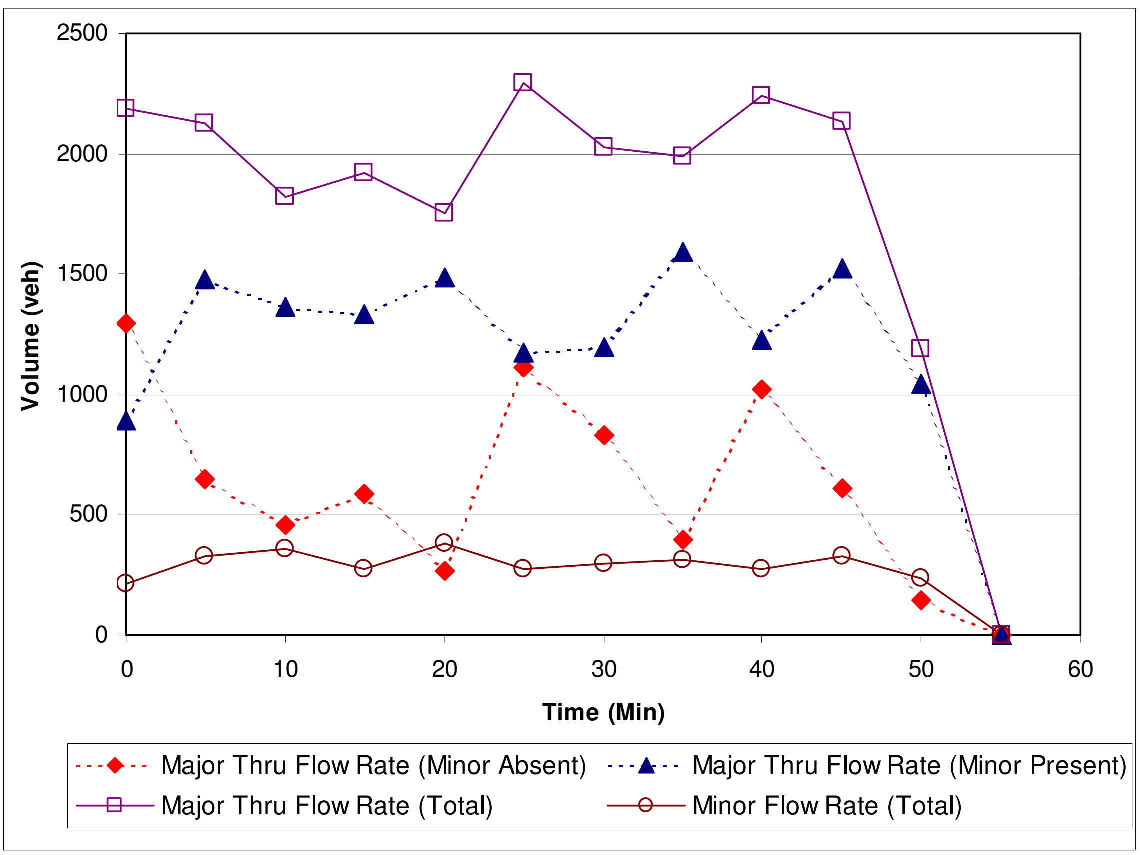
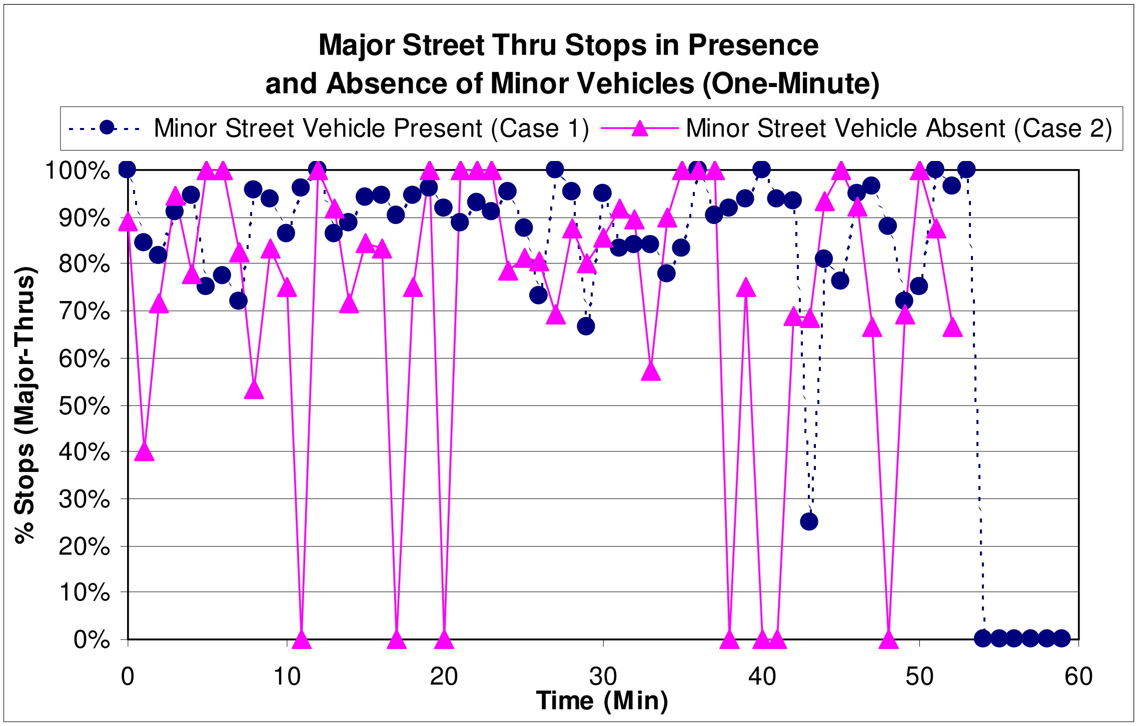


Figure H.1 Five-Minute Presence and Absence Analysis at Piedmont Rd./The Prado



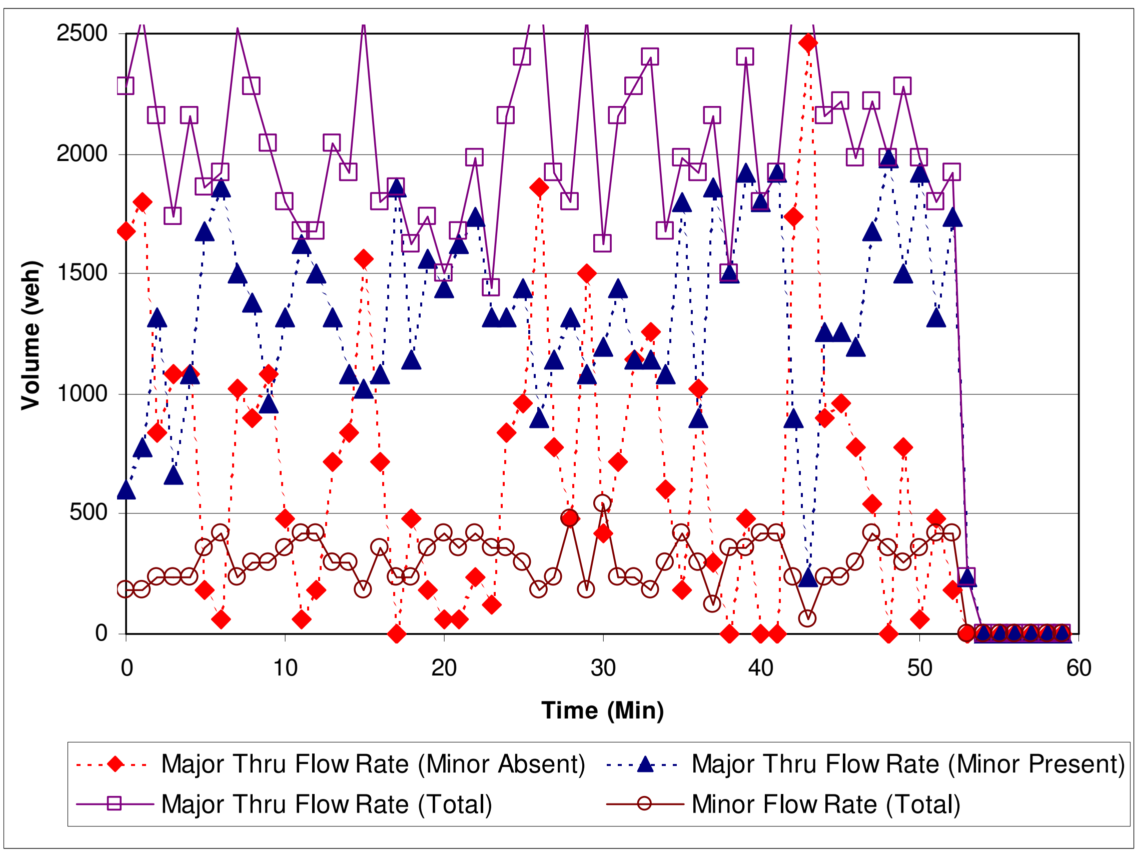
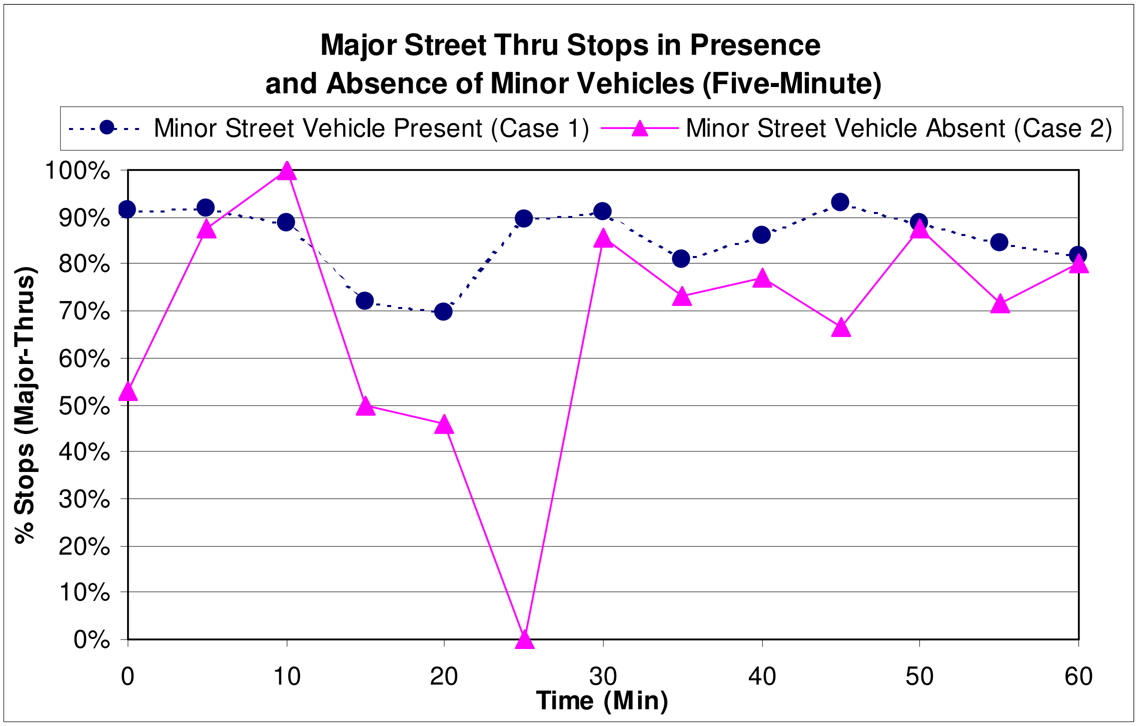


Figure H.2 One-Minute Presence and Absence Analysis at Piedmont Rd./The Prado



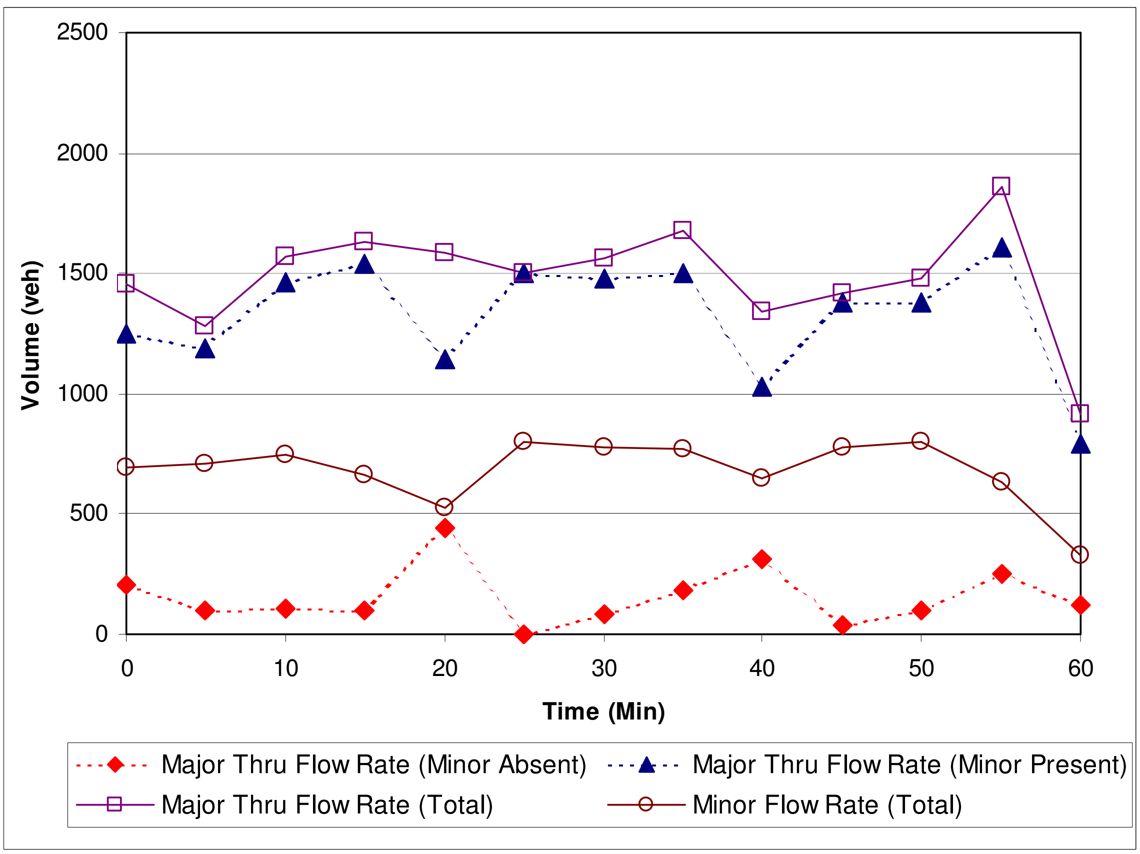
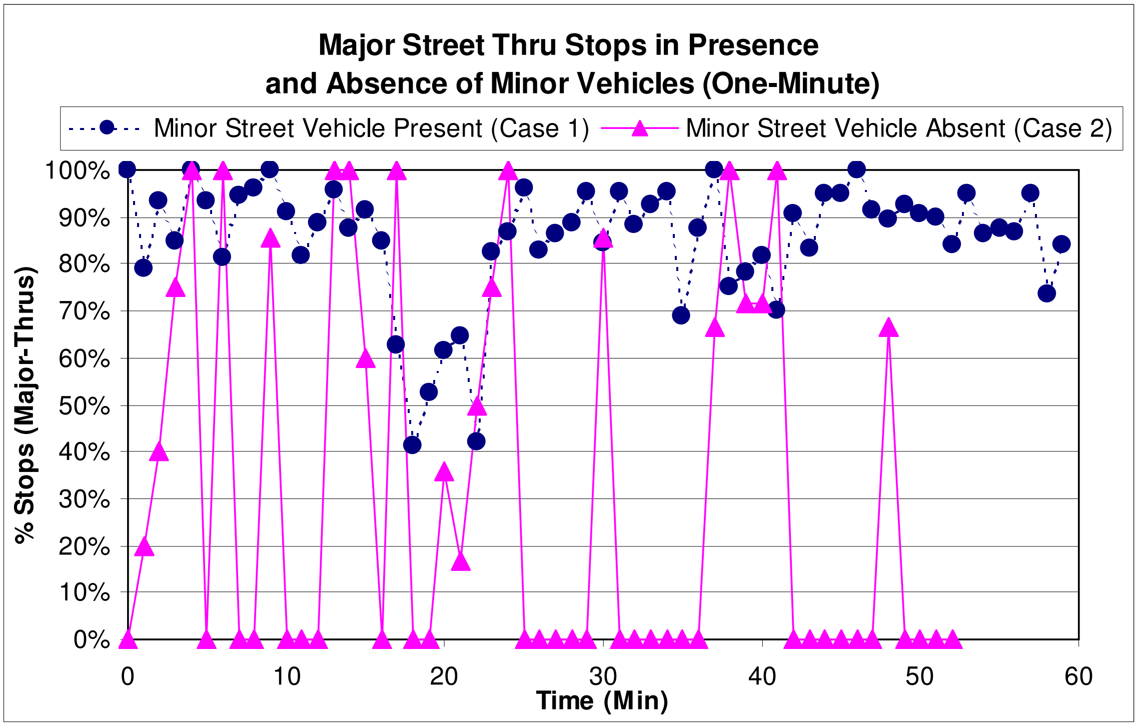


Figure H.3 Five-Minute Presence and Absence Analysis at Roswell Rd./W. Wieuca Rd.



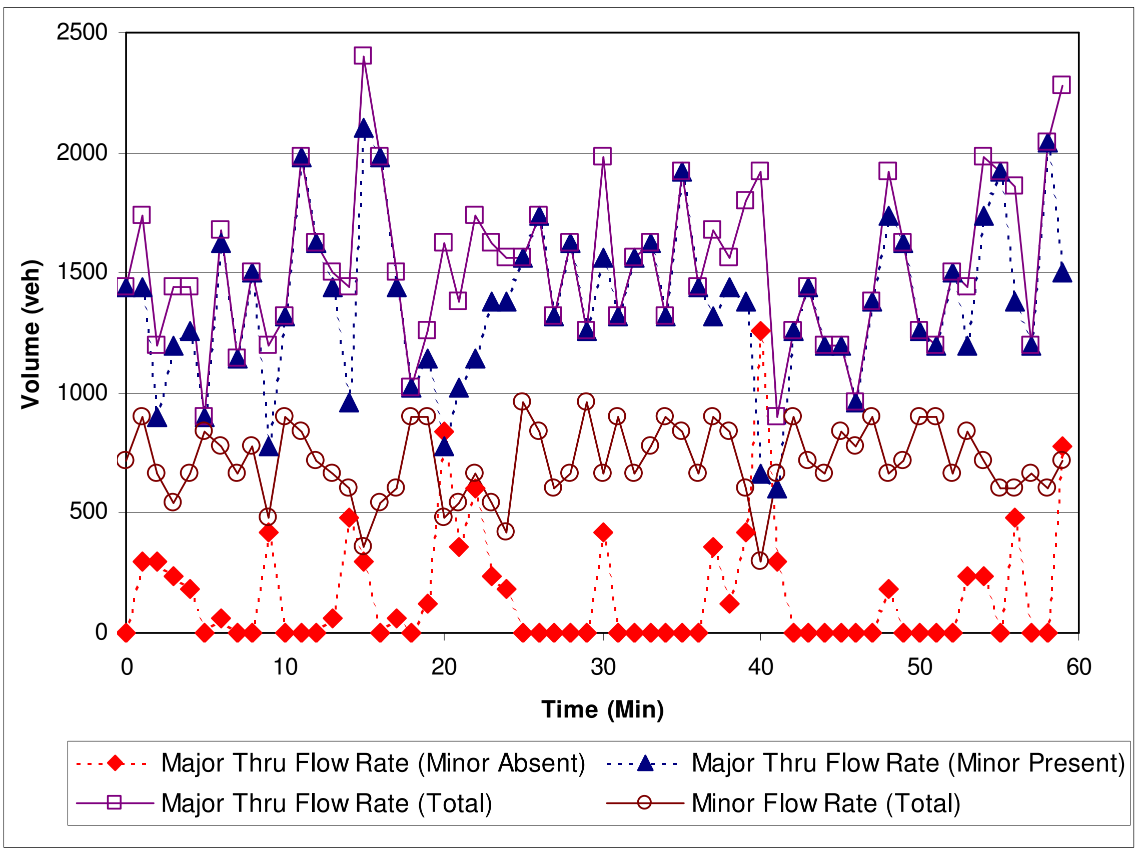


Figure H.4 One-Minute Presence and Absence Analysis at Roswell Rd./W. Wieuca Rd.

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